

GEOLOGY AND PETROLOGY OF THE FLETCHER LIMESTONE COMPANY
QUARRY, FLETCHER, HENDERSON COUNTY, NORTH CAROLINA

by

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TABLE OF CONTENTS

ABSTRACT.....	vii
ACKNOWLEDGMENTS.....	viii
DEDICATION.....	ix
LIST OF TABLES.....	x
LIST OF FIGURES.....	xi
LIST OF PLATES.....	xiv
INTRODUCTION.....	1
Study Objectives.....	3
Methods.....	3
Terminology.....	5
Geologic Setting.....	6
Eastern Blue Ridge.....	8
Inner Piedmont.....	9
Brevard fault zone.....	10
PETROLOGY OF THE FLETCHER MARBLE AND ADJACENT ROCKS.....	12
Quaternary Sediments.....	12
Fletcher marble.....	12
Mineralogy.....	15
Microtextural features.....	37
Brevard phyllonite.....	42
Mineralogy.....	42
Textural features.....	61

Exotic rocks.....	67
Brittle features.....	70
STRUCTURAL ELEMENTS.....	75
Planar Structures.....	75
Continuous schistosity of the Brevard phyllonite.....	75
Fletcher marble shape fabric and lattice preferred orientation foliation.....	75
Crenulation cleavage foliation.....	77
Color banding.....	77
Joints and fractures.....	77
Stylolites.....	81
Lineations.....	83
Fold Structures in the Brevard phyllonite.....	86
Intrafolial folds	86
Mesoscopic folds.....	86
Fold Structures in the Fletcher marble.....	86
Brittle faults.....	89
COMPARATIVE PETROGRAPHY OF SIMILAR CARBONATES.....	95
Linville Falls.....	95
Bandana marble.....	103
METAMORPHIC HISTORY.....	106
Pressure-temperature systems used for interpretation.....	106

Geothermometry and Geobarometry.....	112
Upper amphibolite facies mineral assemblages in the Brevard phyllonite.....	112
Exotic rock metamorphic mineral assemblages.....	113
Lower amphibolite facies assemblages within the Brevard phyllonite.....	114
Lower amphibolite facies mineral assemblages in the Fletcher marble.....	114
Greenschist facies assemblages in the Fletcher marble.....	117
Dolomite and calcite twin geothermometry.....	118
Vein-filling mineralization in the Fletcher marble.....	118
Regional Correlations.....	119
PROTOLITH OF THE FLETCHER MARBLE.....	121
Prior Assumptions Regarding the Fletcher marble.....	122
Shady Dolomite.....	123
Knox Dolomite.....	123
Carbonate Facies within the Tallulah Falls Metamorphic Suite.....	124
CONCLUSIONS.....	126
REFERENCES CITED.....	128
APPENDIX. ECONOMIC GEOLOGY.....	135

ABSTRACT

The Fletcher marble is a fault bounded tectonic slice positioned within the Brevard fault zone of southwestern North Carolina. A Neoproterozoic to Early-Cambrian carbonate facies within the Tallulah Falls Metamorphic Suite is proposed as a protolith to the Fletcher marble. The Fletcher marble contains a mineral assemblage consisting of dolomite + calcite + quartz + white mica \pm chlorite \pm talc \pm tremolite \pm wollastonite \pm graphite. The Fletcher marble is entrained within the Brevard phyllonite. Both are polydeformed and display features associated with ductile and brittle deformation. The Fletcher marble is texturally a marble protocataclasite, however, it contains an earlier protomylonite to mylonite fabric. The earliest deformation recognized within the Fletcher marble is Late-Acadian to Early-Alleghanian mylonitization. Fabric features that display west to southwest-directed dextral shear that are observed in the Brevard phyllonite are correlated to mylonite fabrics in the Fletcher marble. Microscale cataclasis overprints this mylonite fabric, and is associated with the transition from ductile to brittle faulting. Reverse faulting, dip-slip to the northwest, is considered to represent last motion of the fault during the Late-Alleghanian. The Fletcher marble achieved amphibolite facies metamorphism prior to mylonitization as indicated by the presence of tremolite within the protomylonite fabric. Retrograde greenschist facies metamorphism, associated with Alleghanian deformation, overprints the earlier amphibolite facies features.

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My field research would not have been possible if not for the patience and cooperation of Ms. Barbara Stevens and Mr. John Brooks, who own and manage the Fletcher Limestone Company quarry. They allowed me the freedom to work within the quarry and gave me access to unpublished data, which I keep in their trust. I sincerely hope that my work will aid you in your endeavors.

A special thanks go to my mother and brother who helped me along the way. I am sure they are exhausted by my academic struggle, and are quite relieved that they lived to see this through. Also a special thanks to Ms. Jennifer Rohde, for her love and friendship.

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Lastly, I wish to thank the men of 3rd Platoon, C-Company 1/252 Armor for their efforts during OIF II. We have a bond of brotherhood that will never be broken.

DEDICATION

I would like to dedicate this work to my grandmother, Alba Kaltenbach, whose love and support meant more to me than she would ever know.

LIST OF TABLES

Table	Page
1. Modal analyses results for the Fletcher marble.....	20-21

LIST OF FIGURES

Figure	Page
1. Location map of the study area.	2
2. Relative location of field stations in study area.....	5
3. Geologic map of the Skyland 7.5-Minute quadrangle, modified from Dabbagh (1981, Fig. 1 and Fig. 2).....	7
4. Fletcher marble in outcrop.....	13-14
5. Calcite-dolomite distribution within the Fletcher Limestone Company quarry.....	16
6. Stylolites in the Fletcher marble.....	17
7. Mesoscopic textures within the Fletcher marble.....	18-19
8. Photomicrographs of carbonate fabric elements in the Fletcher marble.....	23-24
9. Twin morphologies in the Fletcher marble.....	25-26
10. Photomicrographs of vein-filling carbonate in the Fletcher marble.....	28-29
11. Photomicrographs of quartz within the Fletcher marble.....	30-31
12. Photomicrographs of phyllosilicates within the Fletcher marble.....	34-35
13. Photomicrographs of tremolite within the Fletcher marble.....	36
14. Fletcher marble microtextures.....	38-39
15. Textural features of the Brevard phyllonite in outcrop.....	43-44
16. White mica and its occurrence within the Brevard phyllonite.....	45-46
17. Quartz and its occurrence within the Brevard phyllonite.....	48-49
18. Biotite and its occurrence in the Brevard phyllonite.....	51-52
19. Sillimanite-bearing microcline and plagioclase feldspar porphyroclasts within the Brevard phyllonite.....	53-54
20. Cordierite porphyroclasts and zircon grains within the Brevard phyllonite.....	55-56

21.	Dolomite porphyroclast in the Brevard phyllonite.....	57
22.	Vein-filling mineralization in Brevard phyllonite.....	59-60
23.	Matrix microtextures within the Brevard phyllonite.....	62-63
24.	Mica fish and shear-band cleavage within the Brevard phyllonite.....	64-65
25.	Diagram showing the relative locations of exotic rocks entrained within the Brevard phyllonite in the study area.....	68-69
26.	Relict high-grade mineralogy within selected exotic rocks.....	71-72
27.	Fractures within the Brevard phyllonite.....	73-74
28.	Stereogram of the schistose foliation within Brevard phyllonite.....	76
29.	Lattice preferred orientation within the Fletcher marble.....	78
30.	Stereogram of crenulation cleavage within the Brevard phyllonite	79
31.	Stereogram of color banding within the Fletcher marble.	80
32.	Jointing in the Brevard phyllonite and Fletcher marble.....	82
33.	Slickenlines orientations within the Fletcher marble.....	84
34.	Fold axes within study area.....	85
35.	Mesosopic fold axes within Brevard phyllonite	87
36.	Folds within the Fletcher marble.	88
37.	Orientation of boundary faults in study area.....	90-91
38.	Sketch drawings of outcrop scale faulting within the Fletcher marble.....	93-94
39.	Location map of the Clinchfield Lime Company quarry.....	96-97
43.	Shady Dolomite outcropping in the abandoned Clinchfield quarry.....	99-100
44.	Fabric elements within Shady Dolomite recovered from the abandoned Clinchfield quarry.....	101-102
45.	Photomicrographs of the Bandana marble.....	104

46.	Phase diagram for mica reactions in metapelites.....	107
47.	Phase diagram for reactions involving staurolite and quartz in metapelites.....	108
48.	Phase relationship in dolomitic marble containing excess dolomite and calcite, redrawn from Bucher and Frey (1994, figure 6.2).....	109
49.	Phase relationship in marble containing excess calcite and quartz, redrawn from Bucher and Frey (1994, figure 6.3).....	110
50.	Pressure and temperature diagram showing path of retrograde metamorphism that is recorded within the mineral assemblages of the rocks from the study area.....	111

LIST OF PLATES

Plate	Page
A. Geologic Map and Cross Sections of the Fletcher Limestone Quarry, Fletcher, North Carolina.....	back cover

INTRODUCTION

A body of marble, informally referred to as the 'Fletcher marble' lies within the Brevard fault zone near Fletcher, North Carolina. The Fletcher Limestone Company (Figure 1) currently mines the Fletcher marble for crushed stone and ultra-fine calcium carbonate. The Fletcher marble is economically significant because it is one of the few carbonate deposits in western North Carolina. The origin of the marble is problematic in that it is a mobilized block within a fault zone. Commercial development of the Fletcher marble and nearby marble deposits resulted in the production of agricultural lime as early as 1835 (see Appendix).

Early workers that studied the Fletcher marble described it in terms of its economic significance and lithology. Watson and Laney (1906) tested quarried marble for chemical impurities and noted that a number of joints crosscut the rock. Keith (1907) mapped the Fletcher marble as a lentil-shaped body that was included within his Brevard Schist. Loughlin and others (1921) recognized compositional domains within the Fletcher marble, the presence of outcrop-scale folds, and meter-scale faults that crosscut the rock. In addition, they indicate that talc, tremolite, and wollastonite are present as vein-filling mineralization and scaly coatings along fracture surfaces. Ingle (1947) visited a number of marble deposits along strike with the Fletcher marble and concluded that the Fletcher marble may be part of a continuous carbonate horizon within the Brevard fault zone. Exploratory drilling by the Tennessee Valley Authority (TVA) found additional marble deposits in the Cane Creek drainage several kilometers northeast of Fletcher, N.C. (TVA, 1965, 1966).

Recent workers investigated the Fletcher marble and similar deposits in South Carolina during their research into the geologic history of the Brevard fault zone. Reed and Bryant (1964) recognized that the Fletcher marble was fault bounded and suggested its origin as an exotic slice

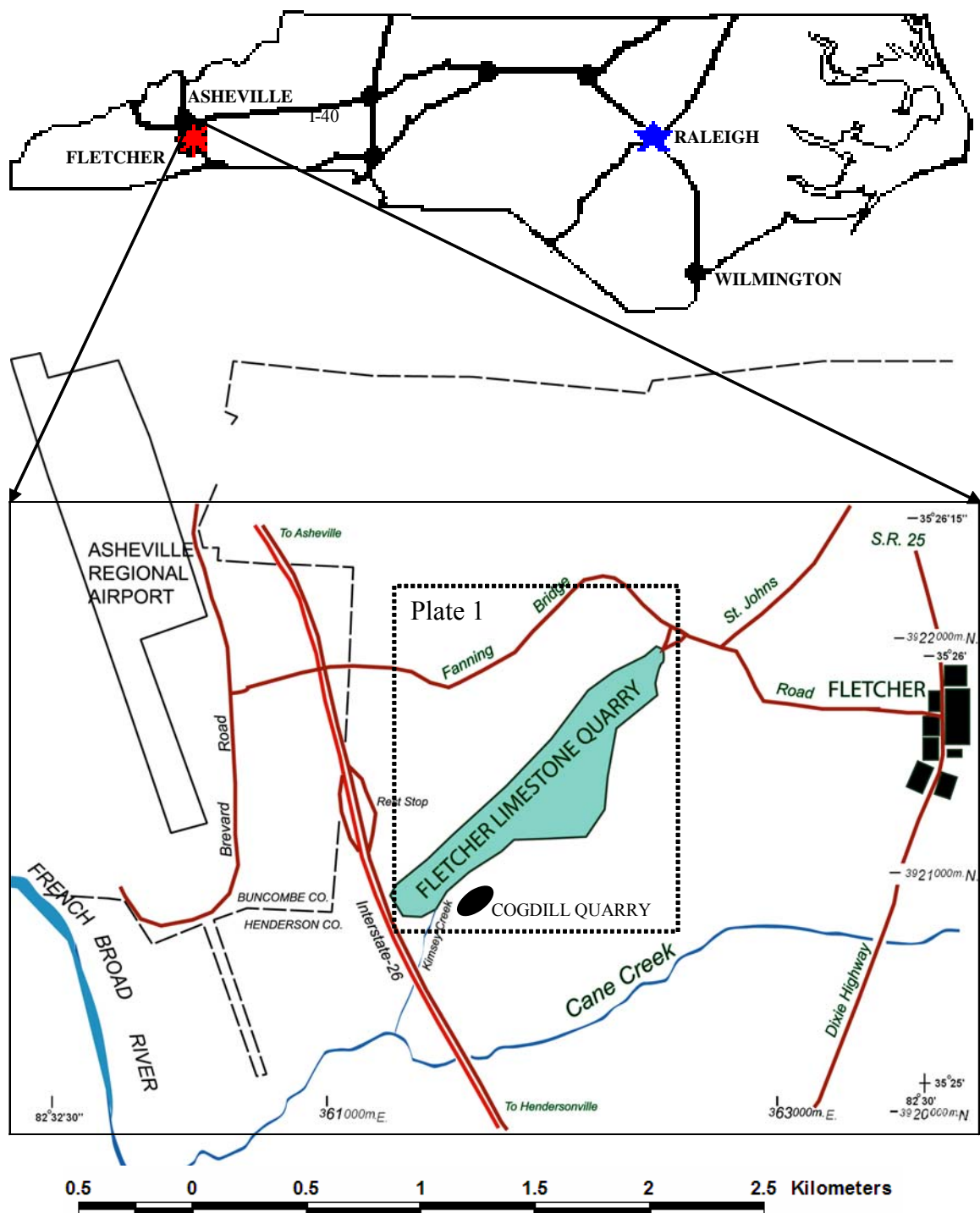


Figure 1. Location map of the study area. Dashed line designates approximate location of Plate 1.

of the Shady Dolomite transported laterally along the Brevard fault zone by strike-slip faulting. Dabbagh (1975, 1981) described the marble during his geologic mapping of the Skyland 7.5-minute quadrangle. Hatcher (1971) suggested that the Fletcher marble and similar deposits are thrust emplaced horse blocks. Hatcher and others (1973) indicated that the Fletcher marble and similar exotic blocks were chemically distinct from samples of the Shady Dolomite. Their analysis indicated that the marble sustained paleotemperatures ranging from 298°C to 383°C, which they interpreted to represent short-term frictional heating. Bobyarchick and others (1988), Liu and Hatcher (1989), and Liu (1991) suggest that the marble originated from the subthrust Paleozoic platform, based in part, upon regional seismic profiles of the Appalachian orogen. High-angle reverse fault slickenlines within the Fletcher Limestone Company quarry led Liu (1991) to infer that the marble was a tectonically emplaced sliver that originated from the Upper-Cambrian-Lower Ordovician Knox Group.

Study Objectives

The objectives of this study are to provide a detailed description of the petrology of the Fletcher marble, determine its structural and metamorphic history and evaluate potential protoliths for the marble.

Methods

The author conducted a reconnaissance survey of the region with Dr. James Dockal and Mr. Brad Worley during the fall of 1999 in order to become familiar with the regional geologic setting. Structural features including foliations, joints, fold axes, mineral lineations, and slickenlines were measured using a Brunton Pocket Transit at 180 field stations (Figure 2, Plate

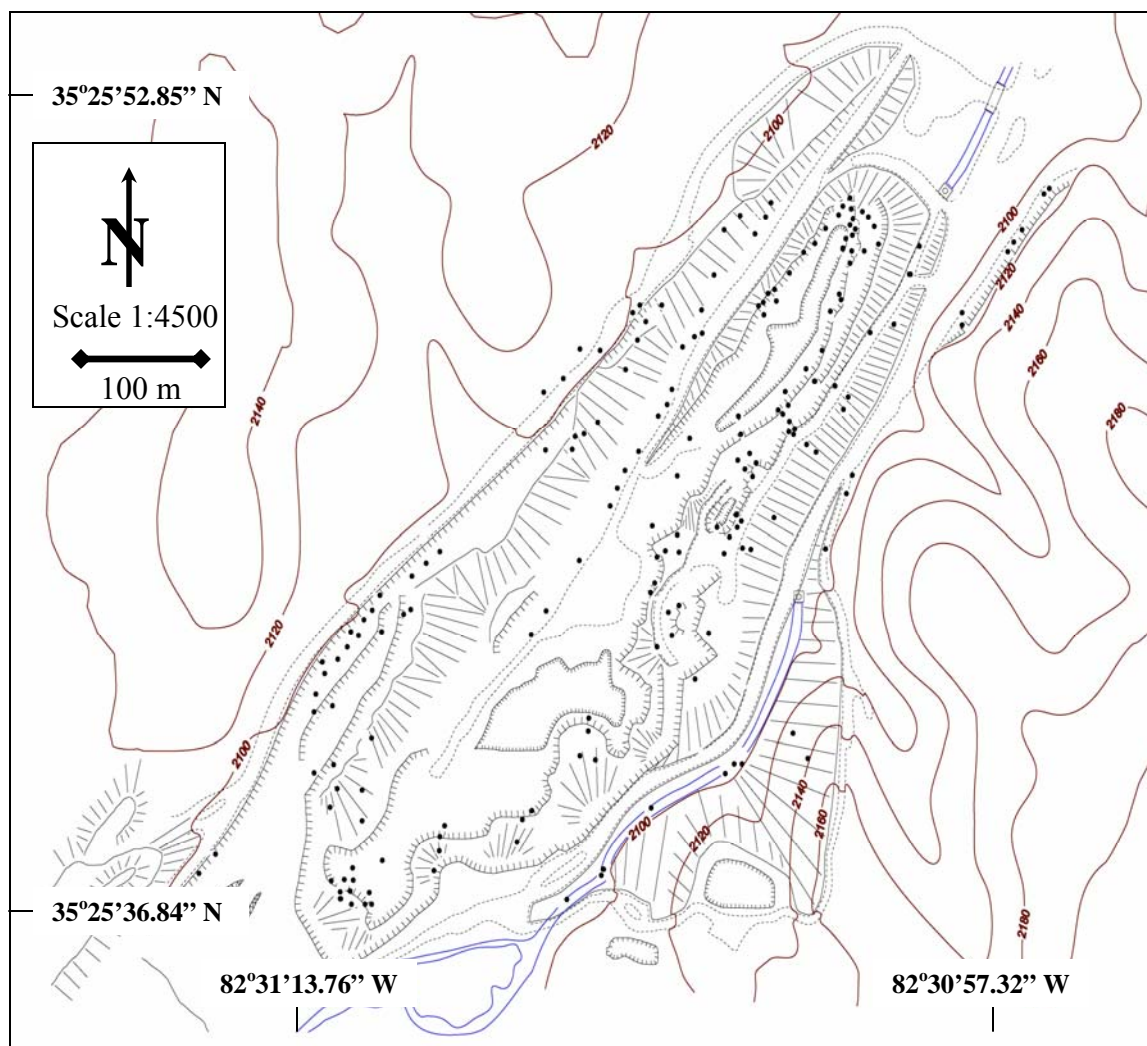


Figure 2. Relative location of field stations within the study area.

A). The author constructed a 1:4,500-scale geologic map of the Fletcher Limestone Company quarry from the field data collected during four field visits between 2001 and 2005 (Plate A). Forty-three oriented and thirteen grab samples were taken from the Fletcher Limestone Company quarry, of which, 67 thin sections were prepared. Thin sections were stained with Alizarin red-S by the method of Dickson (1966) in order to differentiate calcite from dolomite. All thin sections were examined using an Olympus BH2 petrographic microscope. A 250 to 300-count modal analysis was conducted on a mechanical stage, using a random selection interval, for each thin section. A small number of the thin sections were examined using a Leitz petrographic microscope equipped with a four-axis universal stage in order to determine if a lattice preferred orientation was present in the marble. Metamorphic pressure and temperature constraints were estimated using published mineral assemblage associations (Bucher and Frey, 1994) and the calcite twin- plane morphology method of Burkhard (1993). An attempt was made to recover microfossils from acidized samples of the marble, however none were found. Sampling of the Shady Dolomite and Bandana marble was also conducted during this study. In addition, Dr. James Dockal made a small number of thin sections from the Knox Dolomite, Murphy marble, and Gaffney marble available to the author.

Terminology

The naming of lithodemic units follows guidelines established by Article 40 of the North American Stratigraphic Code (2005). Lithic names specified herein are common and familiar, regardless of structural or tectonic interpretation. The term “Fletcher marble” refers to the carbonate rock exposed within the Fletcher Limestone Company quarry, and the nearby Cogdill quarry. The term “Brevard phyllonite” refers to the micaceous rocks that surround the “Fletcher

marble” within the Brevard fault zone. Petrographic description terminology used here is consistent with the North American Geologic-Map Data Model Science Language Technical Team, 2004 (SLTTM 1.0 (2004)). The term “white mica” refers to all phyllosilicates that have optical properties similar to and indistinguishable from muscovite. The term “graphitic” refers to the presence of a mineral substance that in hand sample displays the physical properties suggestive of graphite.

Geologic Setting

The primary field site of this study is the Fletcher Limestone Company quarry, currently operated by the Fletcher Limestone Company (Figure 1). The study area is located within the Skyland 7.5-Minute quadrangle, 1.6 kilometers west of Fletcher, N.C. on Fanning Bridge Road, 1.5 kilometers east of the Asheville Regional Airport, and 15 kilometers south of Asheville, N.C. The quarry lies between the French Broad River to the west, and Kimsey Creek and Cane Creek to the south (Figure 1). Recent quarry operations have diverted Kimsey Creek to prevent flooding of the active workings. It now flows into the inactive Cogdill quarry that lies southwest of the Fletcher Limestone Company quarry.

The Fletcher Limestone Company quarry is situated within the Brevard fault zone. This linear, 2 km wide regional-scale shear zone separates the Eastern Blue Ridge, from the Inner Piedmont in the Skyland 7.5-minute quadrangle (Figure 3). The Eastern Blue Ridge and Inner Piedmont are polydeformed thrust sheets that formed during the evolution of the Appalachian orogen (Odom and Fullager, 1973, Rankin, 1975, Hatcher and Goldberg, 1991, Stewart and others, 1997). The amount of crustal shortening accommodated by these thrust sheets has been variously estimated to be between 200 km (Horton and Zullo, 1991) and 350 km (Hatcher,

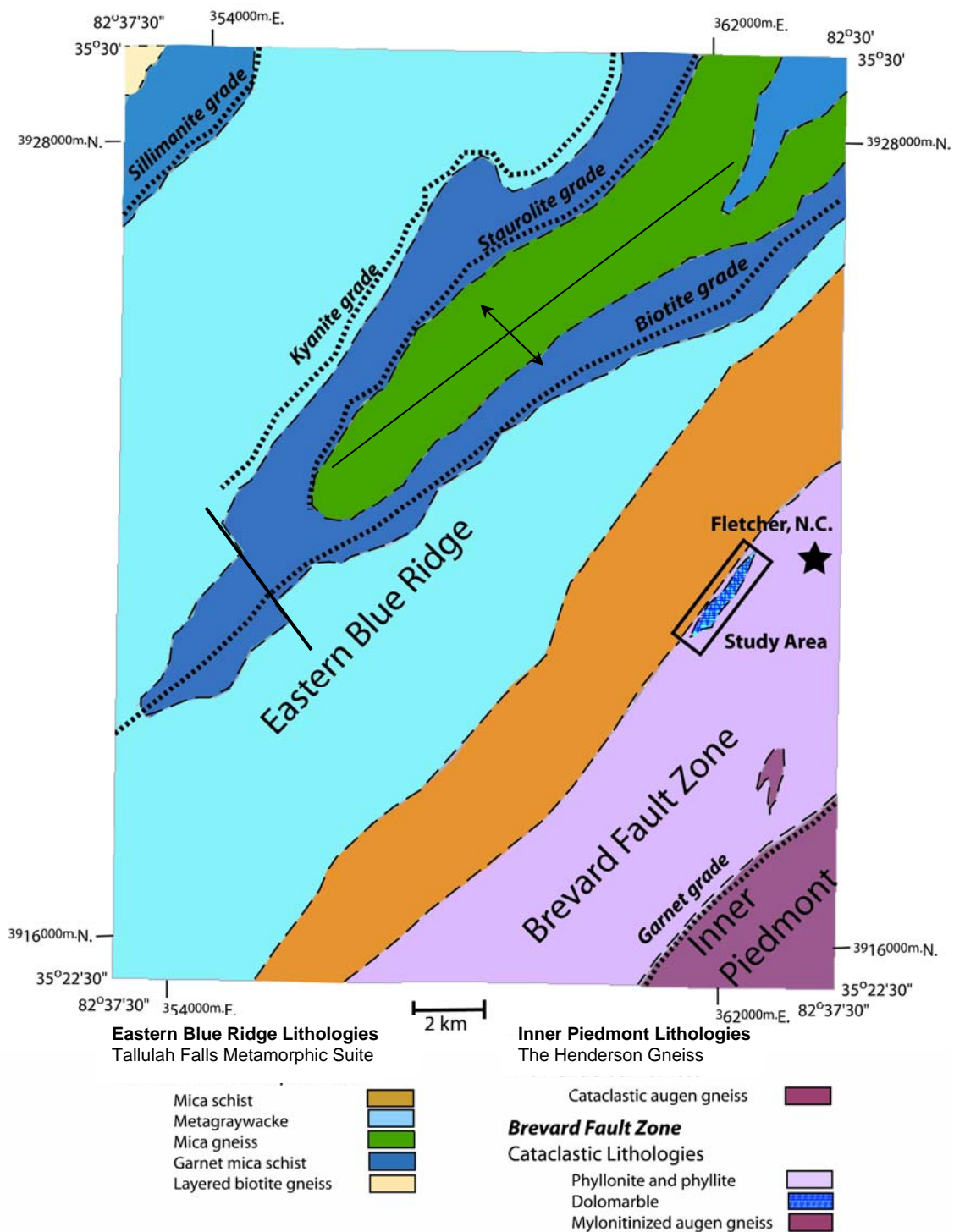


Figure 3 Geologic map of the Skyland 7.5-Minute quadrangle, modified from Dabbagh (1981, Fig. 1 and Fig. 2).

2001), with orogen parallel displacement that may exceed 200 km (Merschhat and others, 2005). Brittle reactivation of the Brevard fault zone is estimated to have resulted in at least 10 km of northwest-directed displacement (Hatcher, 2001).

Eastern Blue Ridge

Dabbagh (1975, 1981) mapped medium to high-grade metamorphic rocks outcropping northwest of the Brevard fault zone in the Skyland 7.5-minute quadrangle. These rocks belong to the Tallulah Falls Metamorphic Suite, in the sense of Raymond and others (1989). Galpin (1915) named the unit the Tallulah Falls quartzite for exposures of Late Proterozoic quartzite and schist exposed in Georgia. Hatcher (1971) later revised the name to Tallulah Falls Formation, which was further geographically constrained by Higgins and others (1988). The rock types observed by Dabbagh (1975, 1981) include layered biotite gneiss, garnet mica schist, mica gneiss, paragneiss and metagraywacke, mica schist, and discontinuous bodies of amphibolite, ultramafic rocks, and pegmatite (Figure 3). Accessory minerals that he observed include staurolite, kyanite, graphite, titanite, and zircon (Dabbagh, 1975). Acker (1982), Horton (1982), Morrow (1977), Worley (2000), and Dockal (2007) have characterized similar rock types in the neighboring quadrangles. Hatcher and Goldberg (1991) considered the protolith of the Tallulah Falls Metamorphic Suite to be Late Proterozoic metasedimentary and metavolcanic rocks.

These rocks are polydeformed and sustained at least two episodes of metamorphism (Dabbagh, 1975, Worley, 2000, and Dockal, 2007). Evidence of amphibolite facies, sillimanite zone metamorphism occurs within the rocks in the northwest corner of the quadrangle (Figure 2). Rocks lying within or adjacent to the Brevard fault zone display retrograde greenschist facies

metamorphism and mylonitization. Brittle deformation locally overprints these rocks (Dabbagh, 1975, Dockal, personal communication).

Inner Piedmont

The Inner Piedmont is a composite thrust sheet composed of Neoproterozoic-Early Paleozoic high-grade schist, gneiss, amphibolite, and meta-granitoids (Horton and McConnell, 1991). The Henderson Gneiss is the only Inner Piedmont lithodeme mapped within the Skyland 7.5-minute quadrangle. Dabbagh (1975) described the Henderson Gneiss as a mylonitic augen gneiss that contains biotite, chlorite, quartz, and potassium feldspar augen (Figure 3). Odom and Fullager (1973) reported a crystallization age between 538 and 535 Ma, and suggested igneous protolith for the Henderson Gneiss. Sinha and others (1989) later recalculated this age to 509 Ma. The Henderson Gneiss sustained amphibolite facies metamorphism, but adjacent to the Brevard fault zone evidence of retrograde greenschist facies metamorphism overprints this (Hatcher, 1993). The Henderson Gneiss lies in thrust contact over the rocks of the Brevard fault zone (Davis, 1993, Hatcher, 1993). Ordovician-aged granitoid plutons also intrude the Henderson Gneiss, one of which dated from 438 Ma (Odom and Russell, 1975). The Henderson Gneiss has a complex deformational history that includes a significant amount of dextral shearing (Vauchez and Brunel, 1988, Davis, 1993, Hatcher, 1993, Merschhat and others, 2005). Bream and others (1998) suggest that the protolith of the Henderson Gneiss was a large granitoid diapir that was emplaced by northwest-directed thrusting, followed by extensive southwest-directed transport and elongation.

Brevard fault zone

The Brevard fault zone is a 750 km long, northeast trending linear feature that extends from the coastal plain of Alabama to southwestern Virginia (Hatcher, 2001). The fault zone dips to the southeast and merges with the master decollement beneath the Blue Ridge and Piedmont thrust sheets (Cook and others, 1979). The fault zone is polytectonic in origin (Hatcher, 2001) and contains polydeformed rocks that display fabric elements inherited from the Taconic (Sinha and Glover, 1978, cited in Horton and McConnell, 1991), Acadian (Odom and Fullager, 1973, Bream and others, 2000, cited in Hatcher, 2001), Neoacadian (Merschhat and others, 2005), and Alleghanian (Sinha and others, 1988, cited in Horton and McConnell, 1991, Hatcher, 2001) orogenies. Bobyarchick (1999) summarizes the various studies on the Brevard fault zone.

Arthur Keith (1907) originally described the Brevard Schist to include all rocks now considered to lie within the Brevard fault zone. This included the Fletcher marble. Based upon the presence of marble, Keith (1907) considered the Brevard Schist to be metasedimentary in origin. The schistose rocks have since been variously described as phyllonite and phyllonite schist (Reed and Bryant, 1964), blastomylonite (Higgins, 1971), cataclastic schist, phyllonite, and mylonite (Lemmon and Dunn, 1973), button schist, micaceous phyllonite (Horton, 1974), porphyroclastic diaphthoritic phyllonite (Dabbagh, 1975), and micaceous phyllonite (Worley, 2000). Hatcher (1969, 1970) revised Keith's (1907) formal name 'Brevard Schist' to what he formerly termed the Brevard Phyllite Member of the Chauga River Formation. Hatcher (1970) considered the Chauga River Formation to contain an internal lithostratigraphy that includes a 'Graphitic Phyllite Member', a 'Carbonate Member', and a 'Basal Brevard Phyllite Member'. Hatcher (1971, 2000) includes the Fletcher marble as one of several exotic block lithologies within the Chauga River Formation. Recent terminologies used by Hatcher (2001) to describe the

rocks of the Brevard fault zone include “Brevard phyllonite” and “Graphitic phyllonite”. The Brevard phyllonite displays a well-developed continuous schistosity, contains 40% or more white mica, and is the product of mylonitization. Therefore, the rock meets the classification criteria for a ‘phyllonite’ within the SLTTM 1.0 (2004).

Alleghanian retrograde greenschist metamorphism overprints Acadian amphibolite facies metamorphism in the rocks of the Brevard fault zone (Hatcher, 2001). Post-Paleozoic brittle faulting crosscuts these earlier features (Roper and Justus, 1973, Horton and McConnell, 1991, Bobyarchick, 1999). Late Triassic intrusive dikes also crosscut the Brevard fault zone (Bryant and Reed, 1970). Shear sense indicators are consistently dextral within the Brevard fault zone and the dominant foliation probably developed during the latter stages of ductile deformation and retrograde metamorphism (Bobyarchick, 1983). The total amount of movement that was accommodated by the fault zone is not well constrained, though estimates range from 35 km (Higgins and others, 1988; Bobyarchick, 1999), to 217 km (Reed and Bryant, 1964).

PETROLOGY OF THE FLETCHER MARBLE AND ADJACENT ROCKS

Two lithodemes underlie the study area; the Fletcher marble and the Brevard phyllonite (Plate A). Both are polydeformed and display microscale to mesoscale, ductile and brittle deformational features.

Quaternary Sediments

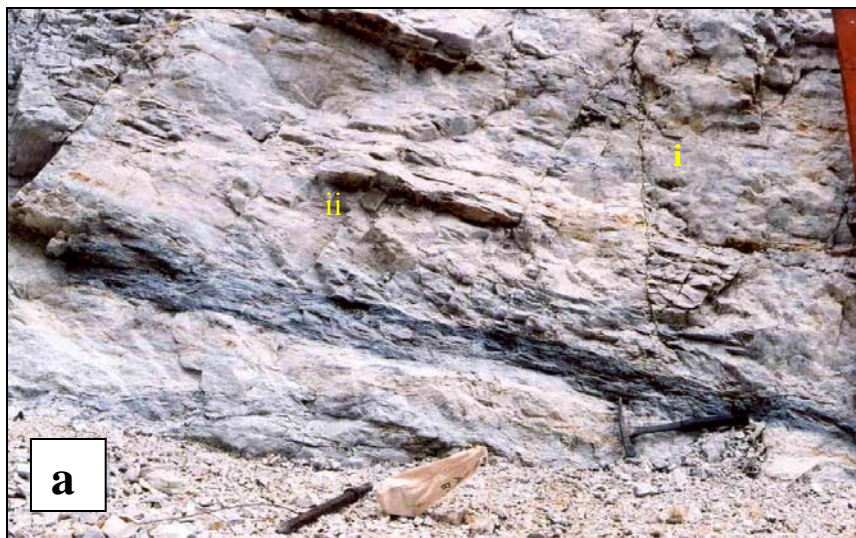
Quaternary sediments conceal the lithodemes southwest and northeast of the study area. The sediments include alluvial and colluvial deposits. Alluvial soils are deposited in the areas adjacent to the French Broad River, Cane Creek, and Kimsey Creek (Plate A). Within the Fletcher Limestone Company quarry, these sediments have been excavated to expose the Fletcher marble.

Fletcher marble

The Fletcher marble is a megascopic, lenticular body of dolomitic and calcitic marble that lies in fault contact with the surrounding Brevard phyllonite (Plate A). The Fletcher marble encompasses the area of the Fletcher Limestone Company quarry and the nearby Cogdill quarry. It pinches out to the northeast into the Brevard phyllonite, while to the southwest it is concealed beneath alluvial deposits. The Fletcher marble is exposed along strike for 1.7 km, and dips 50° southeast into the subsurface to an undetermined depth.

Fresh exposures of the Fletcher marble are typically white, light pink, or very light blue in color and may display dark blue-gray interlayerings that are 1 to 2 cm thick (Figure 4a). Weathered surfaces of the marble commonly exhibit solution weathering or rillenkarren (refer to

Figure 4. The Fletcher marble in outcrop. (a) Fresh exposure of the Fletcher marble containing blue-colored interlayers. Fracturing (i) and jointing (ii) is present in center field of view. The sample bag, hammer and steel chisel are for scale. (b) Solution weathering or rillenkarren on the surface of marble. (c) Broken surface showing the difference in color and texture between weathered and fresh marble. Hammer for scale (0.3 meters).



Environmental Protection Agency, EPA/600/R-02/003, 2002, p. 106) and are light gray to light brown (Figure 4b and 4c).

The Fletcher marble is fine- to medium-grained. It is crosscut by fractures and jointing that allow the rock to break into fragments ranging in size from 1.0 cm to 0.5 m. Coarser-grained marble is present in limited amounts within the southeastern portion of the Fletcher Limestone Company quarry. There is no sedimentary bedding preserved in the marble, and the distribution of calcite and dolomite does not indicate a pre-existing depositional or diagenetic relationship (Figure 5). The marble contains stylolites, which are best exposed within a streambed outcrop near the abandoned Cogdill quarry (Figure 6a-b). The stylolites are 0.5 m to 1.0 m in length and are spaced 2.0 cm to 3.0 cm apart. A light blue to gray coloration banding is present within the Fletcher marble. These bands are intercalated with white marble and have a thickness that ranges from 0.50 millimeters to 1.5 meters (Figure 7a, 4a). Fractures and systematic joint sets are the most noticeable textural features present within the marble (Figure 7b). The spacing between the joints systematically range from 0.5 cm to 15 cm apart. These features have also been previously described as joints (Loughlin and others, 1921, Davis and Hale, 1966), or as fractures (Dabbagh, 1975). Breakage along these discrete planes of weakness produce small rock chips less than 0.5 cm thick, slabs 3-16 cm thick, and blocks 0.5 m in size (Figure 7c).

Mineralogy

The Fletcher marble contains a mineral assemblage of dolomite + calcite + quartz + white mica + chlorite ± talc ± tremolite ± wollastonite ± graphite ± pyrite ± hematite. Modal analysis indicates that the average composition is 66% dolomite, 13% calcite, 14% aphanocrystalline cataclastic material, and 7% other minerals (Table 1).

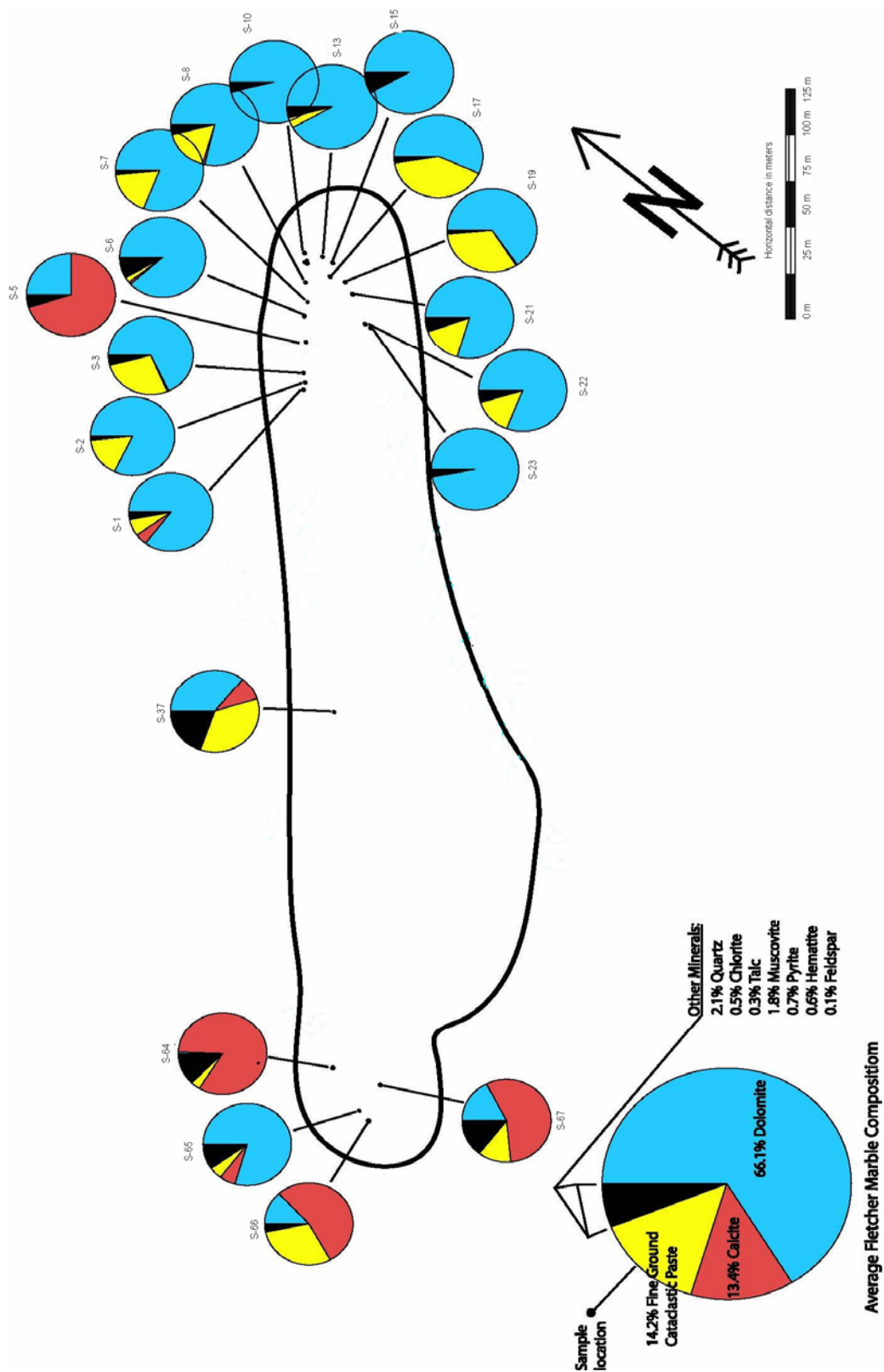


Figure 5. Calcite-dolomite distribution within the Fletcher Limestone Company quarry. Pie charts indicate composition by modal analysis.

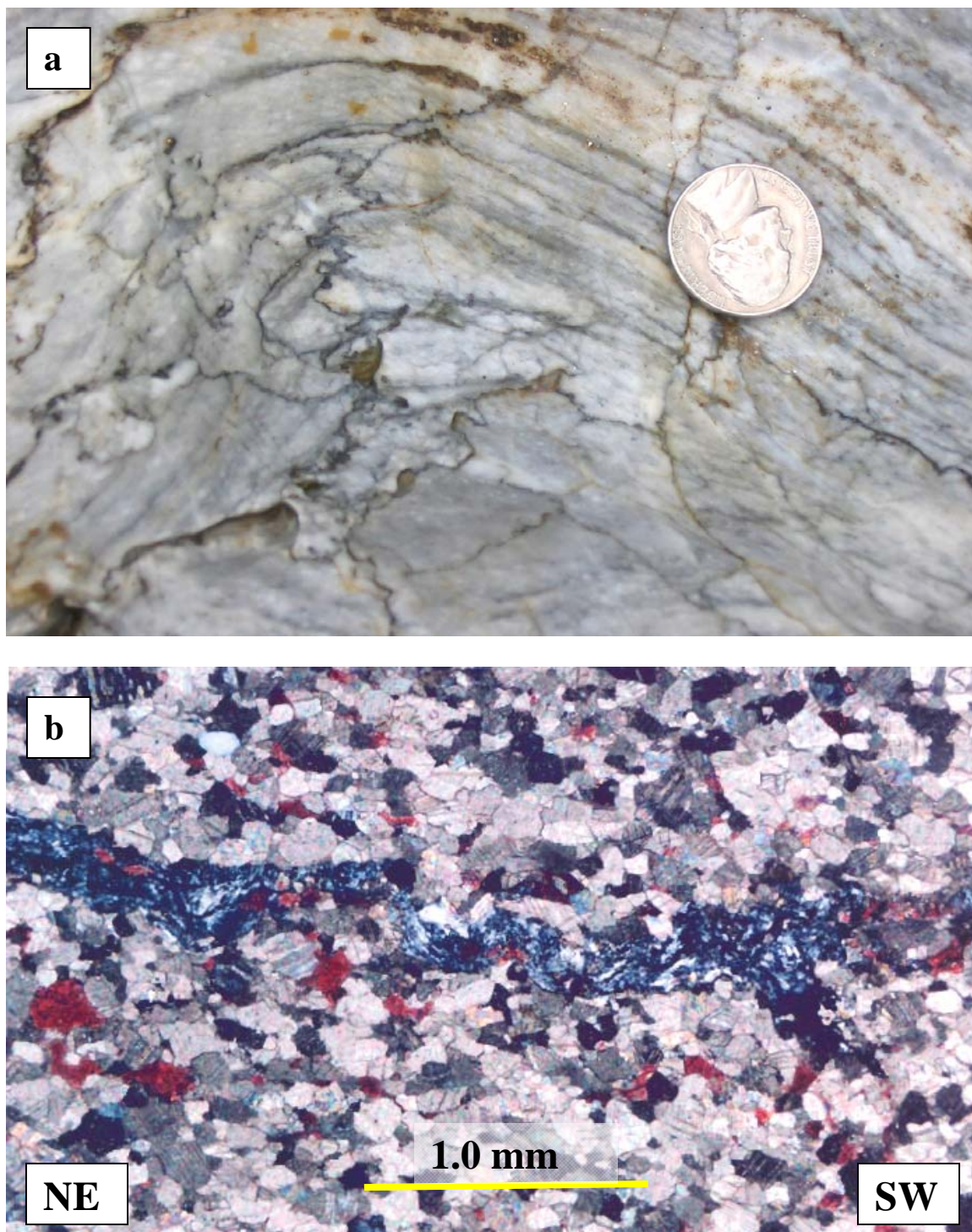


Figure 6. Stylolites in the Fletcher marble. (a) Stylolite crosscutting color banding within a streambedded outcrop. (b) Photomicrograph of calcite marble (stained red) with insoluble stylolite residue. Cross-polarized light; bar = 1.0 mm.

Figure 7. Mesoscopic textures within the Fletcher marble. (a) Color banding within an outcrop of marble in the Kimsey Creek, south side of the quarry. The color banding is crosscut by stylolites (i), Brunton compass and quarter for scale. (b) Jointing in an outcrop of the Fletcher marble. Field pack (ii) for scale, center of picture. View is to the southeast. (c) Close up view of the jointing, different outcrop, with a pen for scale. The joints are approximately 0.5 cm apart.



Sample ID	% Dolomite	% Calcite	% Cataclastic material	% Quartz	% Chlorite	% Talc	% Muscovite	% Pyrite	% Hematite	% Tremolite	% Feldspar	Total %
S-1A	86.9	3.3	7.6	1.0	<0.4%	0.6	n.d.	0.6	n.d.	n.d.	n.d.	100.0
S-1B	84.0	6.1	6.1	1.9	<0.4%	0.6	1.3	0.3	n.d.	n.d.	n.d.	100.3
S-1Comp	85.5	4.7	6.9	1.5	<0.4%	0.6	0.7	0.5	n.d.	n.d.	n.d.	100.2
S-2A	78.3	n.d.	20.7	0.3	<0.4%	n.d.	0.0	0.0	0.1	n.d.	n.d.	99.4
S-2B	69.1	n.d.	8.3	0.3	<0.4%	n.d.	0.0	2.3	n.d.	n.d.	n.d.	80.0
S-2Comp	73.7	n.d.	14.5	0.3	<0.4%	n.d.	0.0	1.2	0.1	n.d.	n.d.	89.7
S-3A	64.9	1.3	27.3	2.0	0.1	2.0	1.3	1.3	n.d.	n.d.	n.d.	100.2
S-3B	71.2	n.d.	27.0	0.7	<0.4%	0.3	0.7	0.1	n.d.	n.d.	n.d.	100.0
S-3Comp	68.1	0.7	27.2	1.4	0.1	1.2	1.0	0.7	n.d.	n.d.	n.d.	100.1
S-5	25.0	70.0	n.d.	2.0	<0.4%	n.d.	3.0	n.d.	n.d.	n.d.	n.d.	100.0
S-6A	92.1	n.d.	2.1	1.5	<0.4%	0.3	2.4	n.d.	n.d.	n.d.	n.d.	98.4
S-6B	85.0	1.9	2.2	4.4	<0.4%	1.9	4.4	2.2	n.d.	n.d.	n.d.	102.0
S-6Comp	88.6	1.0	2.2	3.0	<0.4%	1.1	3.4	1.1	n.d.	n.d.	n.d.	100.2
S-7A	83.9	n.d.	15.2	0.1	<0.4%	0.3	0.6	n.d.	n.d.	n.d.	n.d.	100.1
S-7B	78.2	n.d.	19.9	2.0	<0.4%	0.1	0.0	n.d.	0.1	n.d.	n.d.	100.3
S-7Comp	81.1	n.d.	17.6	1.1	<0.4%	0.2	0.3	n.d.	0.1	n.d.	n.d.	100.2
S-8A	79.6	n.d.	17.3	1.3	0.1	0.6	0.0	n.d.	1.3	n.d.	n.d.	100.2
S-8B	71.4	1.6	14.3	1.3	<0.4%	0.0	1.9	1.3	0.0	n.d.	n.d.	91.8
S-8Comp	75.5	0.8	15.8	1.3	0.1	0.3	1.0	0.7	0.7	n.d.	n.d.	96.0
S-9A	76.2	0.9	18.6	0.6	0.1	0.0	1.9	n.d.	1.9	n.d.	n.d.	100.2
S-9B	74.5	0.3	20.8	0.1	0.1	0.0	2.5	n.d.	1.9	n.d.	n.d.	100.2
S-9Comp	75.4	0.6	19.7	0.4	0.1	0.0	2.2	n.d.	1.9	n.d.	n.d.	100.2
S-10A	95.6	n.d.	0.3	0.1	0.1	0.0	1.7	n.d.	2.3	n.d.	n.d.	100.1
S-10B	95.3	n.d.	0.3	0.1	0.1	0.0	2.5	n.d.	0.6	n.d.	n.d.	98.9
S-10Comp	95.5	n.d.	0.3	0.1	0.1	0.0	2.1	n.d.	1.5	n.d.	n.d.	99.5

Table 1. Modal analysis results for the Fletcher marble. Percentages based on 250-300 count.

If a mineral was not observed during the point count, it is considered 'not detected' (n.d.).

Samples that are grouped together are listed as 'Comp'.

Table 1 Continued

Sample ID	% Dolomite	% Calcite	% Cataclastic material	% Quartz	% Chlorite	% Talc	% Muscovite	% Pyrite	% Hematite	% Tremolite	% Feldspar	% Total
S-13A	89.8	n.d.	3.4	n.d.	0.1	1.5	4.6	n.d.	0.6	n.d.	n.d.	100.0
S-13B	97.3	n.d.	4.8	n.d.	0.0	0.6	0.9	n.d.	0.3	n.d.	n.d.	103.9
S-13Comp	93.6	n.d.	4.1	n.d.	0.1	1.1	2.8	n.d.	0.5	n.d.	n.d.	102.0
S-15A	91.8	n.d.	n.d.	n.d.	0.0	0.1	7.7	n.d.	0.4	n.d.	n.d.	100.0
S-17A	64.9	n.d.	49.2	1.7	n.d.	0.2	0.3	n.d.	0.2	n.d.	n.d.	116.5
S-17B	57.0	n.d.	37.7	0.3	n.d.	2.5	0.0	n.d.	0.6	n.d.	n.d.	98.1
S-17Comp	61.0	n.d.	43.5	1.0	n.d.	1.4	0.2	n.d.	0.4	n.d.	n.d.	107.3
S-19A	63.2	n.d.	33.4	n.d.	n.d.	1.0	0.0	n.d.	0.5	n.d.	n.d.	98.1
S-19B	66.4	1.0	31.0	n.d.	n.d.	0.4	1.0	n.d.	0.2	n.d.	n.d.	100.0
S-19Comp	64.8	0.5	32.2	n.d.	n.d.	0.7	0.5	n.d.	0.4	n.d.	n.d.	99.1
S-21	79.5	<0.4	14.9	4.0	n.d.	n.d.	1.0	0.5	0.1	n.d.	n.d.	100.0
S-22	85.0	n.d.	15.0	3.5	n.d.	n.d.	1.0	n.d.	n.d.	n.d.	0.5	105.0
S-23	97.0	<0.4	<0.4	1.0	<0.4	<0.4	2.0	n.d.	n.d.	<0.4	n.d.	100.0
S-37	35.7	9.3	35.0	9.3	n.d.	n.d.	n.d.	10.3	n.d.	n.d.	n.d.	99.6
S-64	0.6	78.4	3.3	5.4	2.1	n.d.	n.d.	n.d.	4.5	n.d.	n.d.	94.3
S-65	79.5	5.9	4.8	6.9	2.4	n.d.	n.d.	n.d.	0.5	n.d.	n.d.	100.0
S-66	13.1	53.8	29.8	1.3	0.3	n.d.	n.d.	n.d.	1.6	n.d.	n.d.	99.9
S-67	17.5	56.0	12.0	0.3	4.7	n.d.	8.1	n.d.	0.6	<0.4	0.8	100.0
Avg Comp	66.1	13.4	14.2	2.1	0.5	0.3	1.8	0.7	0.6	<0.4	0.1	99.7
Avg D-Comp	78.3	1.4	14.9	2.0	0.2	0.4	1.5	0.9	0.4	<0.4	0.1	99.9
Avg C-Comp	14.1	64.6	11.3	2.3	1.8	<0.4	2.8	<0.4	1.7	<0.4	0.2	98.6

The observed distribution of dolomite and calcite within the Fletcher marble is variable along strike. The northeast side Fletcher Limestone Company quarry contains a higher percentage of dolomitic marble and finely ground cataclastic material. The southwestern side of the quarry workings generally contains calcitic marble and a higher percentage of other minerals (Figure 5).

Dolomite is present as xenotopic, finely-crystalline (0.03 mm) to extremely coarsely-crystalline (7.0 mm) grains within the Fletcher marble. It is a major component within the grain shape fabric of the matrix and the coarser-grained porphyroclasts. The mosaic shape of the aggregate varies from inequigranular-interlobate to seriate-interlobate (Figure 8a, b). Inequigranular-interlobate aggregates are uniform in shape and are dominated by finely crystalline dolomite, while seriate-interlobate aggregates contain a variety of grain sizes. Coarse- to extremely coarsely-crystalline dolomite (0.5 to 7.0 mm) is found within porphyroclasts and domains that display relatively little dynamic recrystallization. The dolomite within these domains contains intracrystalline ghost structures. The ghost structures resemble saddle-shaped or baroque dolomite grains, which may be interpreted to represent some aspect of diagenetic crystallization (Radke and Mathis, 1980). These relict structures are completely enclosed within the coarse- to extremely-coarsely crystalline dolomite, and are crosscut by type-IV twinning in the sense of Burkhard (1993). The grain boundaries of these grains are generally serrated to interlobate, while others display subgrain development of fine- to very finely-crystalline dolomite. The shape fabric is crosscut by cataclastic domains filled with aphanocrystalline dolomite (Figure 8b). The twin morphologies observed in the Fletcher marble (Figure 9) are; type-I (2.7%), type-II (0.1%), type-III (4.2%), type-IV (48.9%), and untwinned grains (34.8%).

Figure 8. Photomicrographs of carbonate fabric elements in the Fletcher marble. (a) An inequigranular-interlobate mosaic of fine-to medium-grained xenotopic dolomite. Note the presence of porphyroclasts (i) mantled by a matrix of finer-grained dolomite (ii). (b) Cataclasite with finely ground dolomite and polycrystalline fragments. (c) Inequigranular-seriate mosaic of fine to medium crystalline calcite. Note the presence of Type-III and -IV twinned grains crosscut by a stylolite (center field of view). All photomicrographs were taken under cross-polarized light; bar = 1.0 mm.

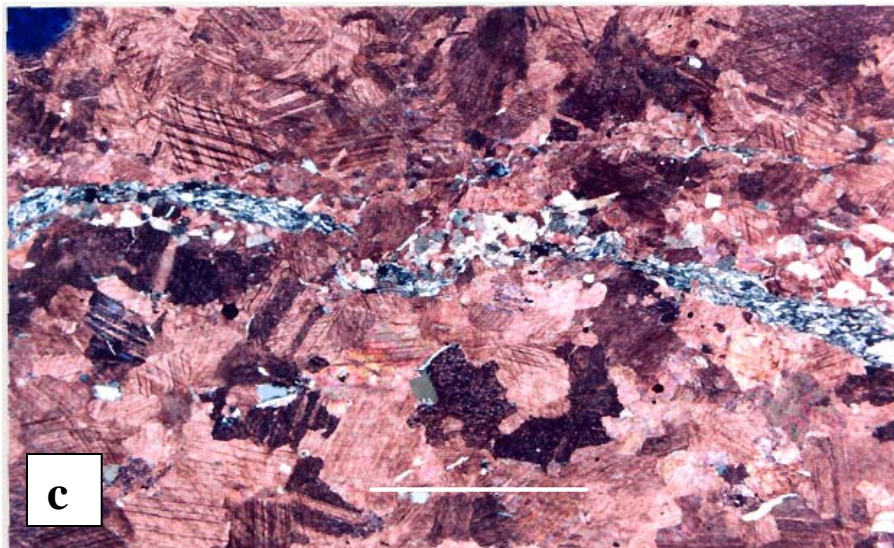
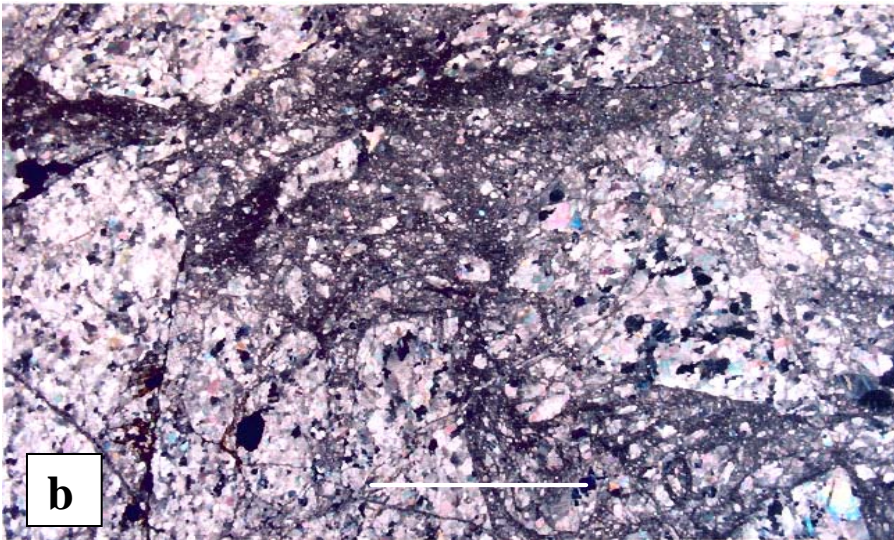
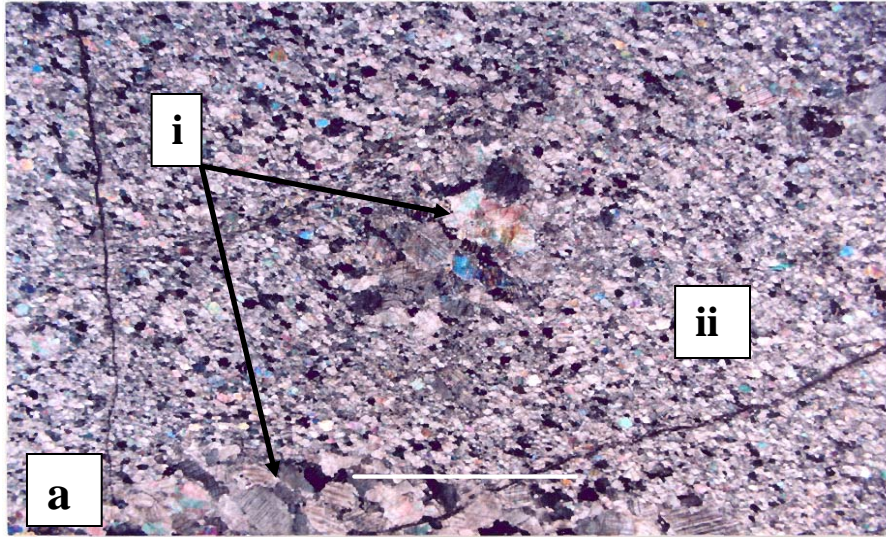
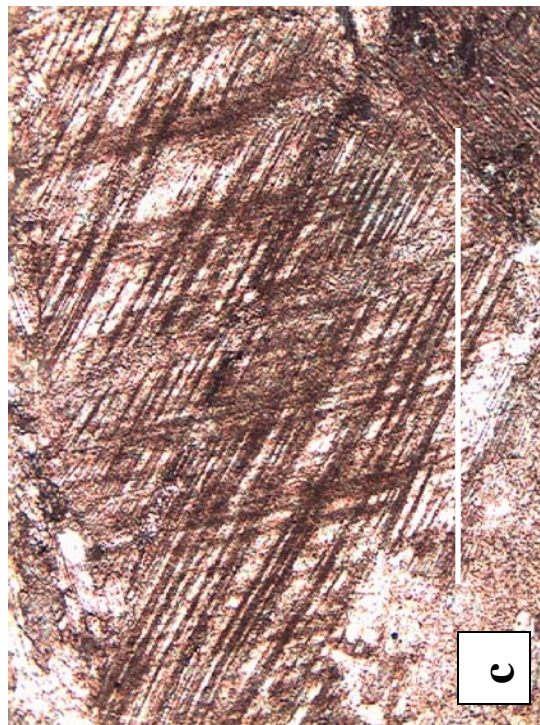
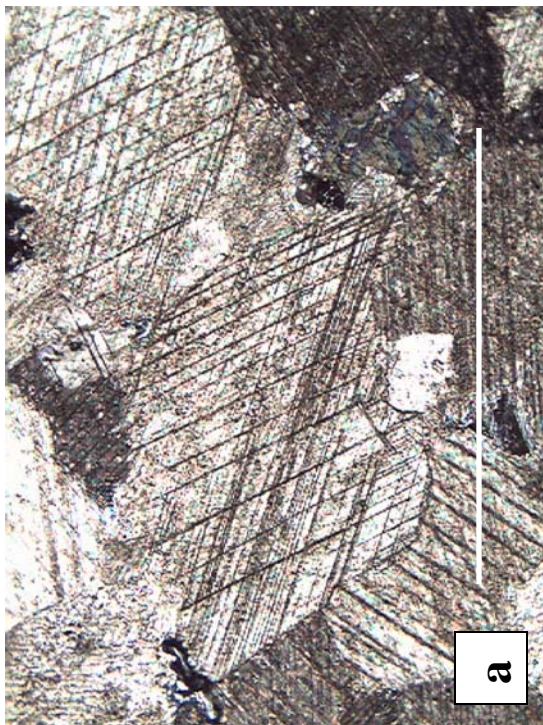
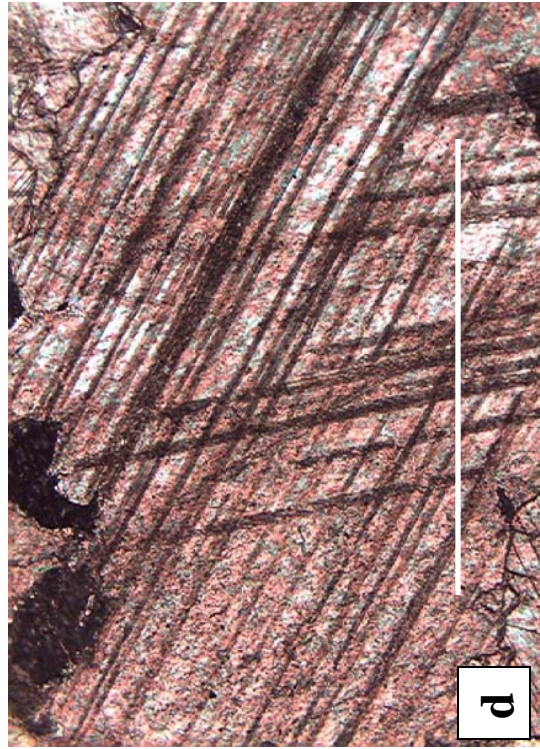


Figure 9. Twin morphologies in the Fletcher marble. a) Type-I twinning. b) Type-II twinning. c) Type-III twinning. d) Type-IV twinning. All of the photomicrographs were taken under cross-polarized light; bar = 0.5 mm. Twin morphologies are classified from Burkhard (1993).



Calcite is a major constituent within the grain shape fabric of the Fletcher marble and it also occurs as a vein-fill within brittle fractures. Intercrystalline calcite is fine- to coarsely-crystalline (0.10 to 0.80 mm), xenotopic and forms aggregate mosaics that are seriate-interlobate to equigranular-interlobate in shape (Figure 8c). Mantling of coarse grains by finer grained calcite or dolomite is common. These grains commonly display type-III or type-IV twinning in the sense of Burkhard, (1993). Calcite also occurs with dolomite vein-fill within hairline (1 to 2 mm) dilatational fractures. Fractures that contain finely-crystalline calcite or dolomite may display a syntaxial fibrous habit that grows normal to the vein wall (Figure 10a). These veins may contain a finely-crystalline quartz zone in their center. A second set of crosscutting fractures contains twinned, sparry calcite or dolomite (Figure 10b, c).

Quartz is present within four distinct situations within the Fletcher marble; within porphyroclasts and protomylonite, intercrystalline grains within the matrix of the shape fabric, as vein-fill, and lastly as euhedral grains with pyrite. Quartz that is present within porphyroclasts and protomylonite is medium-to coarsely-crystalline, xenotopic, and has interlobate grain boundaries. It tends to occur in close association with tremolite, calcite and trace amounts of talc. The matrix of the fine-grained shape fabric of the Fletcher marble also contains finely-crystalline, xenotopic quartz (Figure 11a). This intercrystalline quartz tends to be elongated with the shape fabric of the carbonate and display sweeping extinction. Quartz vein-fill is fine to medium-grained and appears to be related to two different deformational events, one that is ductile and one that is brittle. Vein-fill related to ductile deformation contains medium-grained xenotopic, quartz with interlobate grain boundaries. The quartz appears to have formed syntectonically with the surrounding marble and is mineralized with flame-shaped aggregates of talc, possible wollastonite or chlorite. The veining related to later-stage brittle deformation

Figure 10. Photomicrographs of vein-filling carbonate in the Fletcher marble. (a) Finely-crystalline fibrous dolomite that has crystallized normal to the fracture wall. Photomicrograph taken under plane-polarized light; bar = 1.0 mm. (b) Dilatational fracture that propagated through a prior existing cataclastic domain. The fracture is filled with medium-crystalline sparry dolomite. Note the presence of untwinned and Type-I twinned grains only. Photomicrograph taken under cross-polarized light; bar = 1.0 mm. (c) Crosscutting veins display the relative chronological relationship between the two types of vein-fill. The calcite vein-fill displaying the fibrous habit is crosscut by fractures filled with calcite spar. Photomicrograph taken under plane-polarized light; bar = 1.0 mm.

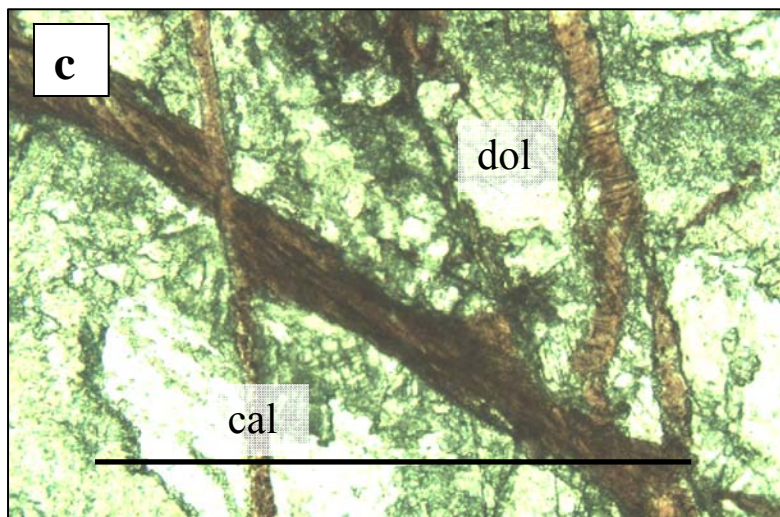
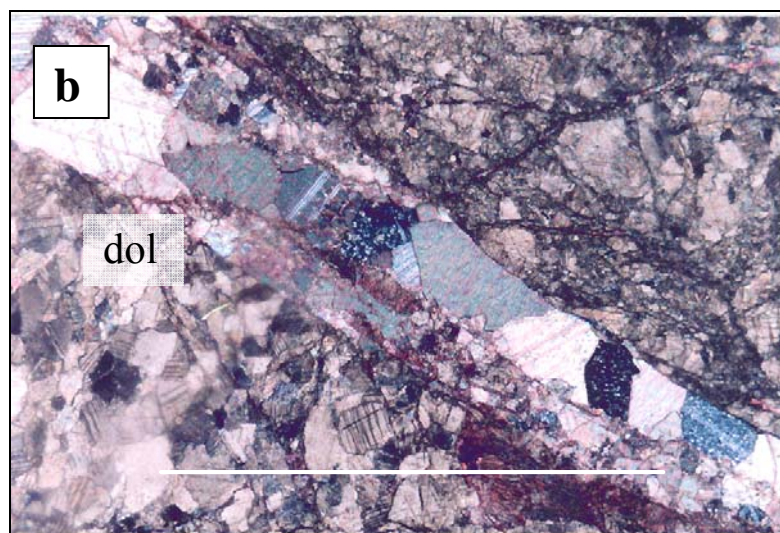
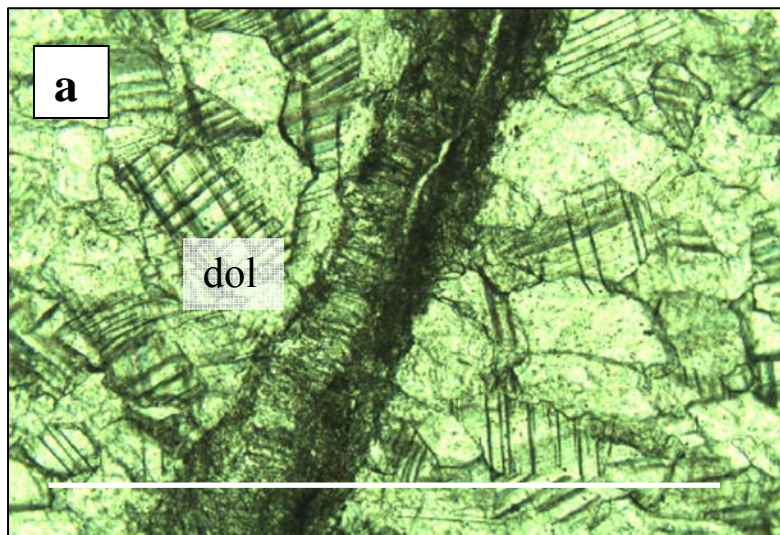
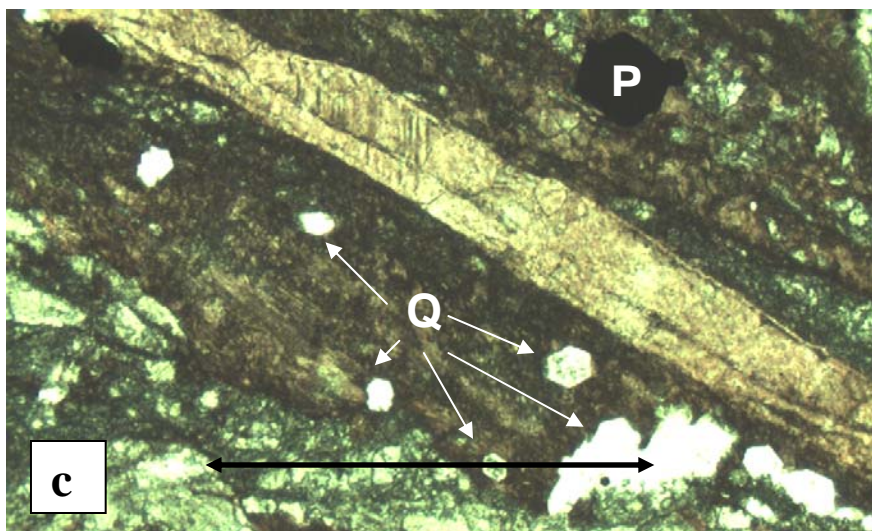
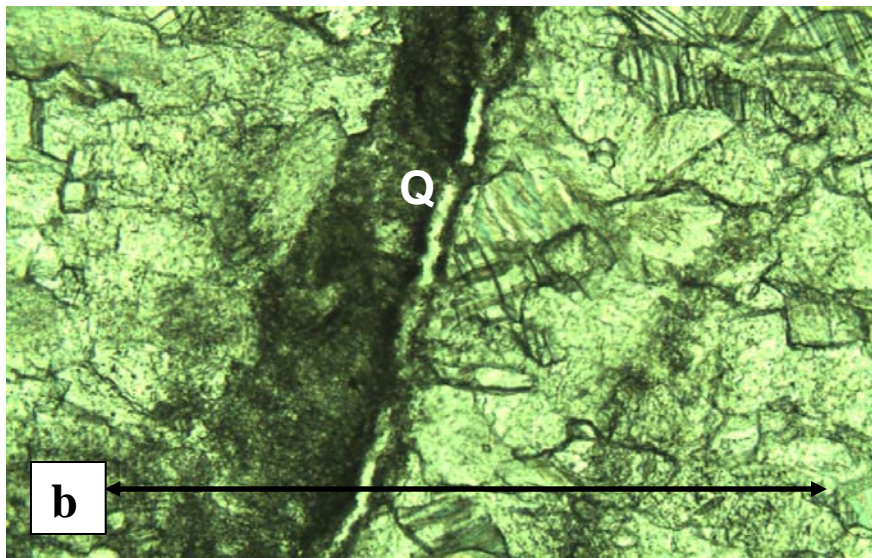
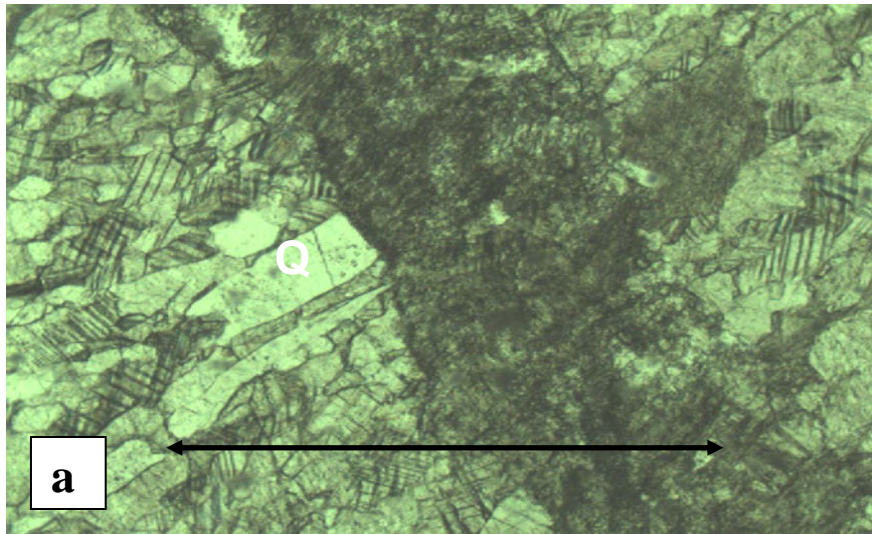


Figure 11. Photomicrographs of quartz within the Fletcher marble. (a) Intragranular xenotopic quartz grains, elongated parallel to foliation. The quartz grain (Q) and the shape-preferred dolomite is crosscut by a cataclastic vein filled with finely-ground material. (b) Millimeter-scale quartz veinlet (Q) that formed within a reactivated cataclastic vein. (c) Photomicrograph of euhedral hexagonal quartz (Q) and pyrite (P) mineralization that postdates the fibrous calcite vein-fill, but predates the sparry dolomite vein-fill. Bar = 1.0 mm, plane-polarized light.



consists of fine-grained quartz zones and veinlets that form within the interiors of fibrous vein-filling calcite (Figure 11b). Late-stage, post-tectonic, euhedral to subhedral quartz forms hexagonal grains with pyrite. This crosscuts the fibrous calcite-filled veins (Figure 10c) and forms finely-crystalline vug-filling druse.

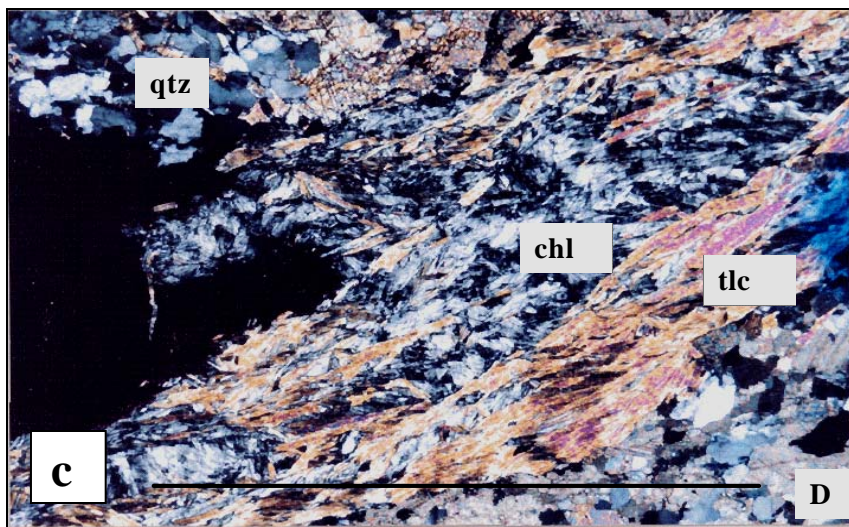
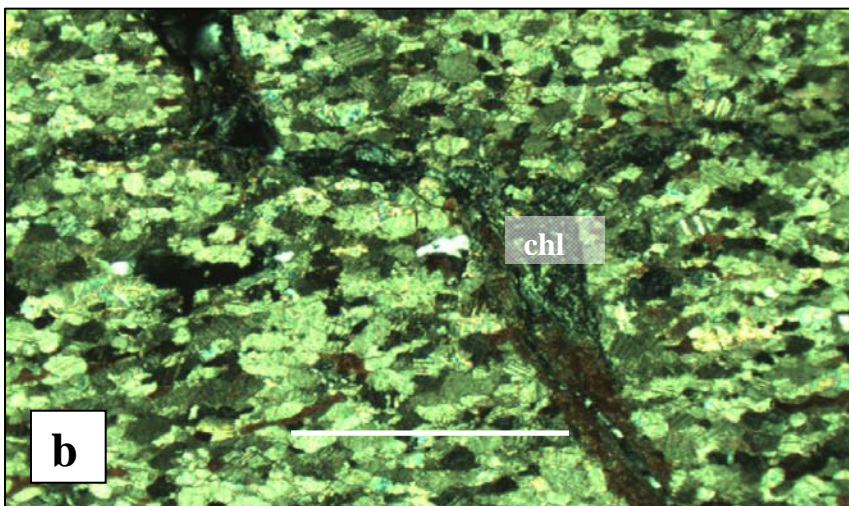
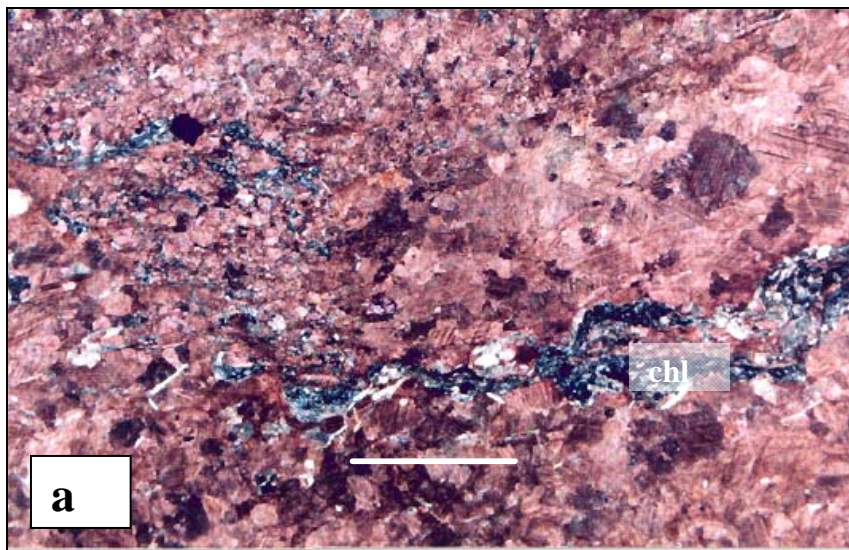
White mica occurs as sparse, individual, fine- to medium-crystalline (0.05 to 0.10 mm) lepidoblastic grains that are interspersed throughout the carbonate. Where a carbonate shape fabric is developed, the white mica forms a weakly developed mica preferred orientation foliation.

Chlorite is present as fine- to medium-crystalline, anhedral (0.013 to 0.25 mm) weakly to non-pleochroic grains. It chiefly occurs in two situations within the Fletcher marble; interleaved with insoluble material within stylolites (Figures 6 and 12a), or as fracture fill within pervasive late-stage jointing (Figure 12b).

Talc is generally sparse in the rock. It usually occurs within the fine-grained shape fabric as fine- to medium-crystalline grains that display a weak lattice preferred orientation foliation. It also forms medium-crystalline (0.05 to 0.20 mm) flame-shaped aggregates that are interleaved with chlorite or wollastonite and xenotopic quartz (Figure 12c). Loughlin and others (1921) report that veining within the Fletcher marble contains wollastonite with quartz, talc, and possible tremolite. However, only one vein containing talc was observed in this study. In hand sample, talc occurs along joint surfaces as fine-grained bladed flakes or scaly coatings.

Graphite displays dark gray color and a soft, greasy feel in hand sample. It is present along joint plane partings as anhedral flakes or films and appears to be a minor mineralogical constituent of the dark blue-gray color banding.

Figure 12. Photomicrographs of phyllosilicates within the Fletcher marble. (a) Stylolite containing chlorite crosscutting the continuous foliation in calcitic marble. Insoluble material and chlorite are in the upper left field of view. (b) Chlorite (chl)-filled fracture that offsets an earlier calcite filled vein. (c) Lensoidal-shaped vein mineralization of flame-shaped talc (tlc) interleaved with chlorite (chl), and xenotopic quartz (qtz). A void created during thin sectioning is to the left. All photomicrographs were taken under cross-polarized light; bar = 1.0 mm in (a) and (b). Bar = 0.5 mm in (c).



Pyrite occurs as euhedral to subhedral cubic and hexagonal crystals that are 0.5-1.0 mm in diameter within the intercrystalline carbonate matrix, brecciated zones, and vein fill (Figure 11c). Linear aggregates of euhedral to anhedral pyrite occur along slickensides, fracture surfaces, and partings. Hematite is present as black to reddish-brown, subhedral cubic pseudomorphs after pyrite (0.5 to 1.0 mm in diameter). Hematite can be found throughout the lithodeme, but may also be found within the color banding and along open fractures. Hematite and limonite occur along partings and open fractures, or as coatings on dolomite spar within small partially filled vugs. Limonite appears as a coating on ghost baroque dolomite grains in thin section.

A trace amount of feldspar (0.2%) was observed in thin section as widely disseminated grains, in association with white mica. Much of the feldspar is however concentrated within the dark blue color banding as described by Loughlin and others (1921). Feldspar grains are subhedral to anhedral in shape, and display weakly developed albite twinning.

Tremolite is observed within coarse- to extremely coarsely-crystalline fabrics within the marble. The tremolite is finely-crystalline, and displays radiating acicular habit (Figure 13a-b).

Loughlin and others (1921) reported that the wollastonite is associated with talc within quartz-filled veins, and they make a limited reference to the presence of tremolite within the vein fill. Wollastonite was not positively identified during the study, however, the presence of it cannot be discounted. Much of the quarry that Loughlin and others (1921) studied has long since been quarried for crushed stone. It is also unclear what the mineralogical relationships were between the wollastonite, tremolite and other minerals. No further information is available as to where these veins occur, but it seems most likely from the literature (Loughlin and others, 1921, Davis and Hale, 1966) that it was located within the southwestern quarry wall (Figure 5). In

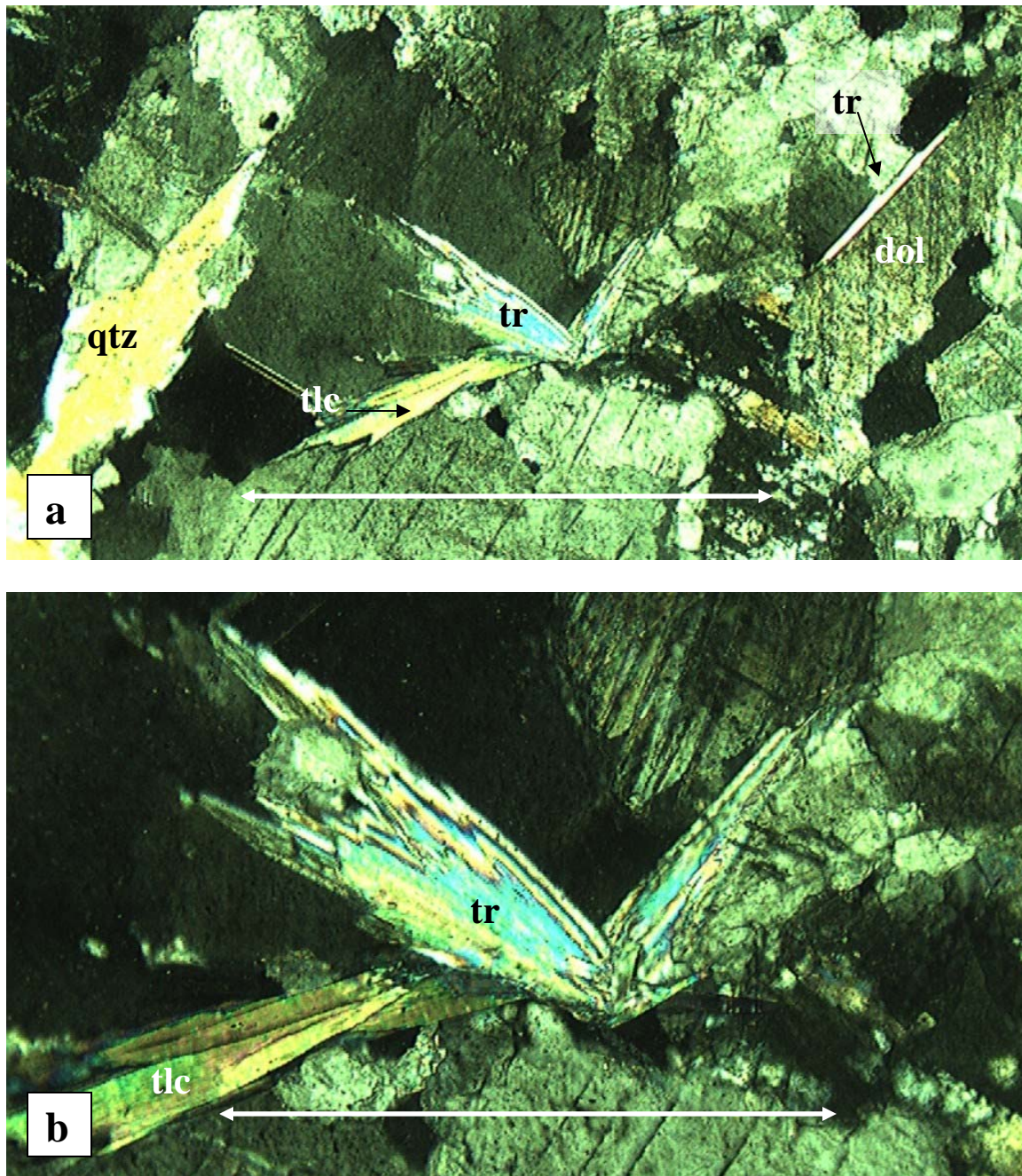


Figure 13. Photomicrographs of tremolite within the Fletcher marble. a) Acicular tremolite occurs as radiating masses and individual blades between grains of dolomite. It has only been observed within domains of protomylonite. Photomicrograph taken under cross-polarized light; bar = 1.0 mm. b) Tremolite appears to occur in close association with talc, possibly indicating incomplete talc-tremolite reaction. Photomicrograph taken under cross-polarized light; bar = 0.5 mm.

addition, galena (Davis and Hale, 1966) and magnetite (Dabbagh, 1981) are also reported within the Fletcher marble, although none of these were observed during this study.

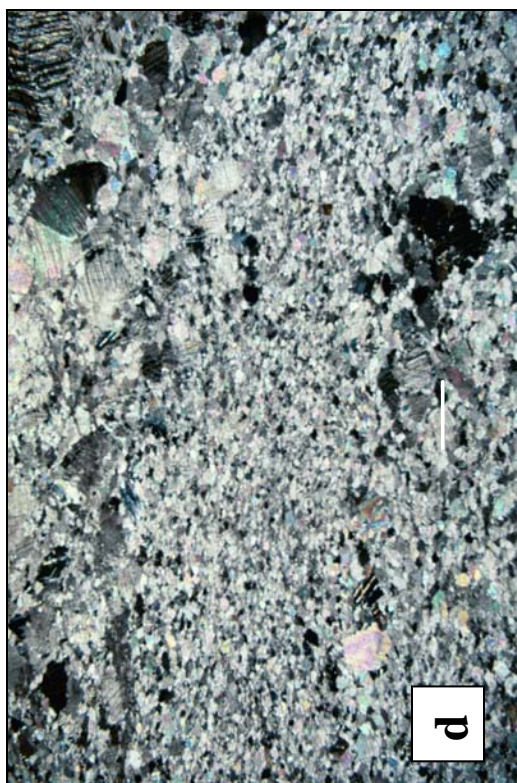
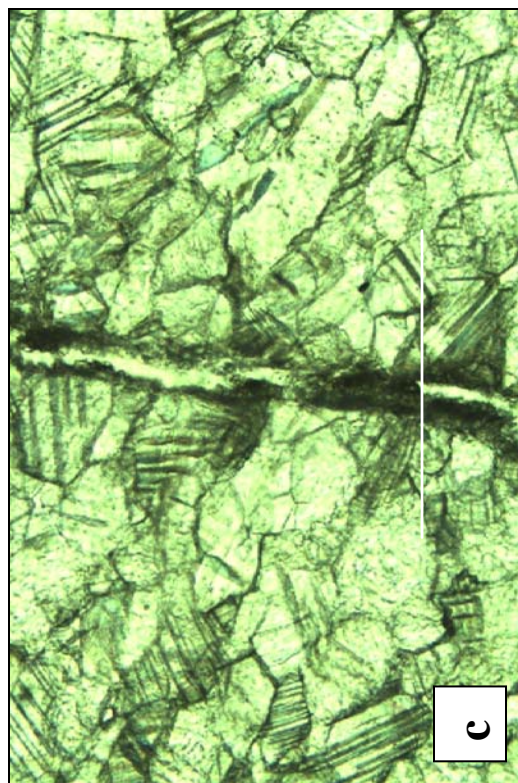
Microtextural features

Microtextural examination of the Fletcher marble indicates that it is primarily a marble protocataclasite as defined by the North American Geologic-Map Data Model Science Language Technical Team (2004), herein referred to as (SLTTM 1.0, 2004). The marble, however, retains an early mylonitic to protomylonitic character. The textural aspects of the marble are described in terms of its early mylonitic fabric, the crosscutting protocataclastic fabric, and late-stage jointing and crosscutting fractures. Furthermore, to better describe the mylonitic fabric, its fabric elements (i.e., protomylonite, mylonite and porphyroclasts) are considered as separate conceptual domains, each of which is defined by the SLTTM 1.0 (2004).

The early mylonitic fabric of the Fletcher marble contains two unique domains that can be defined based upon the degree of mylonitization. One domain contains 10 to 50% matrix and based upon the classification system of SLTTM 1.0 (2004), is a protomylonite. The other domain contains 50 to 90% matrix and is termed a mylonite. On average, matrix composes 65 to 75% of the mylonitic fabric, while porphyroclasts comprise 25 to 35%.

The protomylonite domains are characterized by the presence of centimeter-scale (1 to 5 cm long), elongated porphyroclasts containing extremely coarse- to coarsely-crystalline dolomite (Figure 14a). These grains often contain relict structures (Figure 14a) and are in mineralogical association with quartz and tremolite. The extremely coarse-grained dolomite also displays evidence of dynamic recrystallization along grain boundaries that resulted in subgrain development.

Figure 14. Fletcher marble microtextures. (a) Protomylonitic domain. The porphyroclasts are comprised of extremely coarsely-crystalline dolomite. Contained within the dolomite grains are limonite ghosts after relict baroque dolomite (i). These features are considered to be precursory to mylonitization. Photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (b) Photomicrograph of mylonitic matrix. This grain shape-preferred fabric is the most commonly observed ductile fabric in the marble; overprinting cataclasis has since fractured this fabric. Photomicrograph was taken in cross-polarized light; bar = 1.0 mm. (c) Photomicrograph of polygonal texture within the mylonitic marble. Photomicrograph was taken under plane-polarized light; bar = 0.5 mm. (d) Porphyroclast in the mylonitic domain. These porphyroclasts do not display sense of rotation. Photomicrograph was taken under cross-polarized light; bar = 1.0 mm.



The mylonitic domain contains a shape-preferred fabric consisting of fine- to medium-grained dolomite and calcite (Figure 14b). If the mylonitic domain is matrix- dominated, the shape of the aggregate is inequigranular-interlobate. If there is significant amount of porphyroclasts present, such that the matrix no longer dominates the fabric of the rock, then the shape of the aggregate is inequigranular-seriate.

The matrix (Figure 14b) is the product of continual grain size reduction that is accomplished through twinning, subgrain development and recrystallization of dolomite and calcite grains. The medium-sized grains display mantling by fine to extremely fine carbonate, but on the whole, much of the matrix is uniform in grain size. Weakly defined bands of lepidioblastic white mica forms a weak lattice preferred orientation foliation. This foliation also helps to define the grain-shape fabric of the mylonite domain. A granoblastic texture is observed to a limited degree within the matrix of the mylonite. This texture is comprised of a mosaic of fine- to medium-crystalline, polygonal, equigranular dolomite that displays straight crystal boundaries and triple junctions (Figure 14c). The grains contain little to no twinning or undulatory extinction. This texture is considered a localized aspect of the mylonite where recovery and crystal growth were favored over subgrain development.

The porphyroclasts (Figure 14d) within the mylonite domain measure 0.70 mm to 1.0 cm in diameter, and display no sense of rotation. They are comprised of medium to coarsely crystalline xenotopic dolomite. These grains retain fewer relict features than the extremely-coarsely crystalline dolomite found within the protomylonite domains.

Ductilely deformed veins appear to have formed syntectonically with the mylonitic fabric elements in the Fletcher marble. The veins are filled with medium-crystalline, xenotopic quartz, medium-crystalline, flame-shaped talc aggregates interleaved with medium-crystalline chlorite.

The vein-filling minerals display intergrowth with xenotopic, equigranular-interlobate grains of dolomite (Figure 12c).

Cataclastic fabric elements overprint the mylonitic fabric elements in the marble. The average percentage of aphanocrystalline cataclastic material is estimated to be 14.0% (Table 1), which meets the naming criteria for ‘protocataclasite’ in the SLTTM 1.0 (2004). The microfabric is dominated by intersecting cataclastic veins (0.25 to 1.0 mm) and wider cataclastic zones. These domains contain finely-ground dolomitic to calcitic material, polycrystalline fragments, and recrystallized dolomite rhombohedra. The fabric displays a loss of cohesion in microscale; however, marble appears to retain cohesion between joint planes.

Three generations of crosscutting fractures and joints have been observed to crosscut the Fletcher marble. First generation fractures and joints are filled with fibrous dolomite or calcite (Figure 10a, 10c). They display syntaxial growth normal to the joint or fracture wall. The fibrous vein fill also contain some quartz veinlets (Figure 10a, 11b) that appear to have crystallized within the center of the veins, or along the wall of the host rock. The fibrous calcite may have mineralized syntectonically with the quartz. Fractures filled with finely-crystalline chlorite and displaying small amounts of offset are observed (Figure 12b). A second set of filled fractures is filled with blocky calcite or dolomite (Figure 10b). The calcite displays type-I, -II, and possibly -III twinning while the dolomite is largely untwinned. The third generation of fractures is open and contains no mineralization.

Brevard phyllonite

The Brevard phyllonite occurs in the footwall and the headwall of the fault that bounds the Fletcher marble. Much of the rock has been deeply weathered to saprolite, however fresh exposures occur along the northern fault-line scarp that forms the access ramp to the present quarry pit workings (Plate A). Weathered phyllonite is silver-brown to mottled gray in color and has a dull earthy luster. It commonly degrades into talus piles of fissile rock chips, buttons of clayey white mica, and quartz granules. Fresh exposures of the Brevard phyllonite are light silver-green, blue-gray or dark gray in color, display button-like, schistose foliation and may display localized jointing (Figure 15a, b). The buttons are 2.0 cm to 3.0 cm in size. Small asymmetric (2.0 to 8.0 cm) boudins and meter-scale lensoidal bodies of recrystallized quartz also occur parallel to the schistose foliation. Breakage along joint planes produces slabs of rock that range from 2 mm to 10 cm in thickness.

Mineralogy

The Brevard phyllonite is primarily composed of white mica and quartz, with localized graphitic domains. It contains lesser amounts of chlorite, microcline, sillimanite, cordierite, biotite, zircon, plagioclase, and garnet. Alteration products include sericite, clinozoisite, and epidote. Post-metamorphic mineralization and weathering have produced pyrite, hematite, and iron oxides. The mineralogy of the Brevard phyllonite is described in terms of its fabric elements: matrix, porphyroclasts and crosscutting veins.

The matrix of the Brevard phyllonite is composed predominantly of white mica (>40%). The white mica is lepidoblastic, finely-crystalline (0.05 to 0.10 mm) and is intercalated with chlorite and quartz, forming a prominent continuous schistosity (Figure 16a). The quartz is

Figure 15. Textural features of the Brevard phyllonite in outcrop. (a) Typical outcrop of Brevard phyllonite displaying jointing. Note fine-grained texture. Here, the rock closely resembles a phyllite and contains crosscutting joints (i). (b) Fresh exposure of the Brevard phyllonite displaying a schistose texture. The schistosity has a button-like appearance. View of both photographs is to the northwest, normal to foliation.

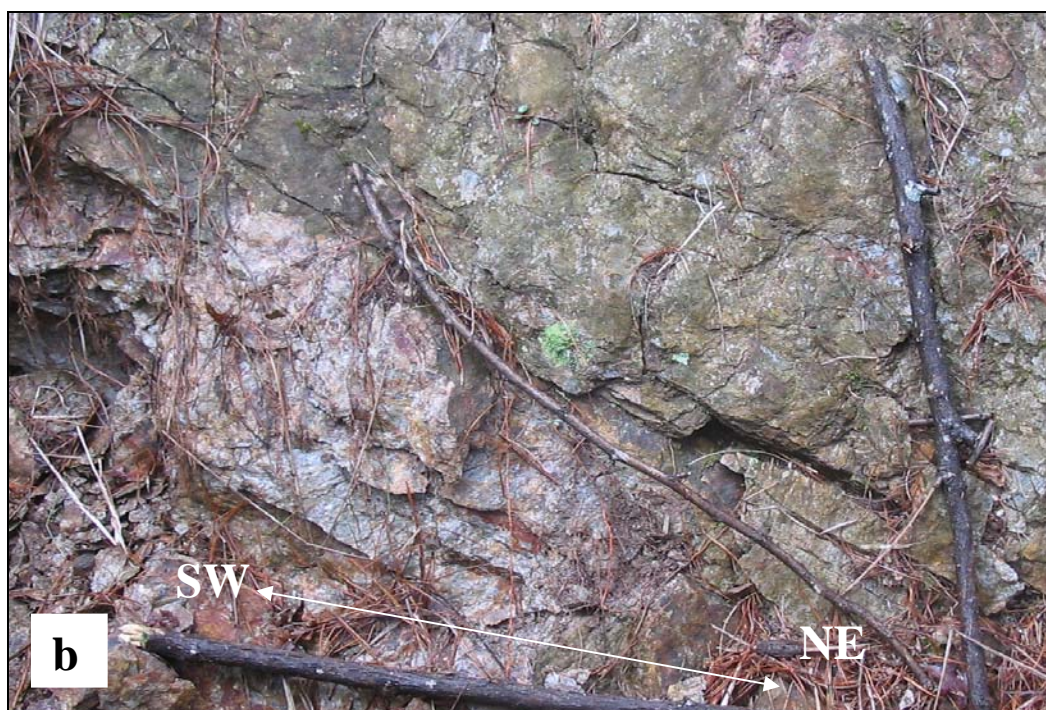
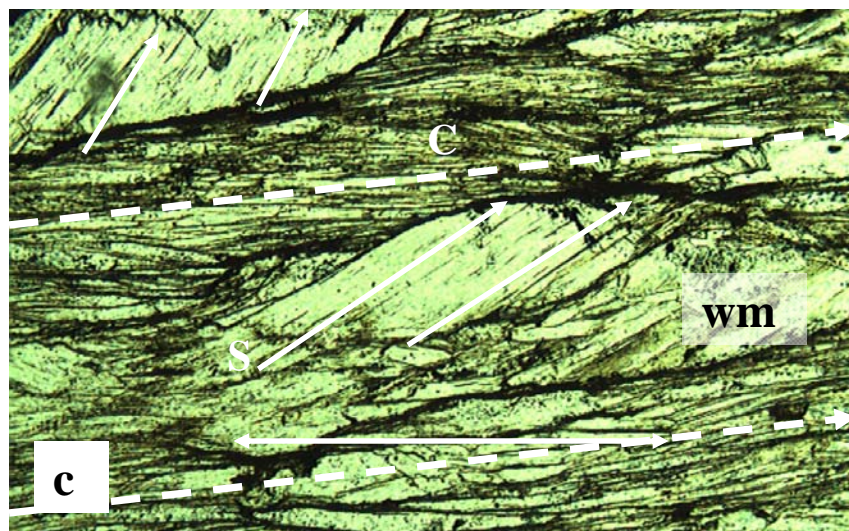
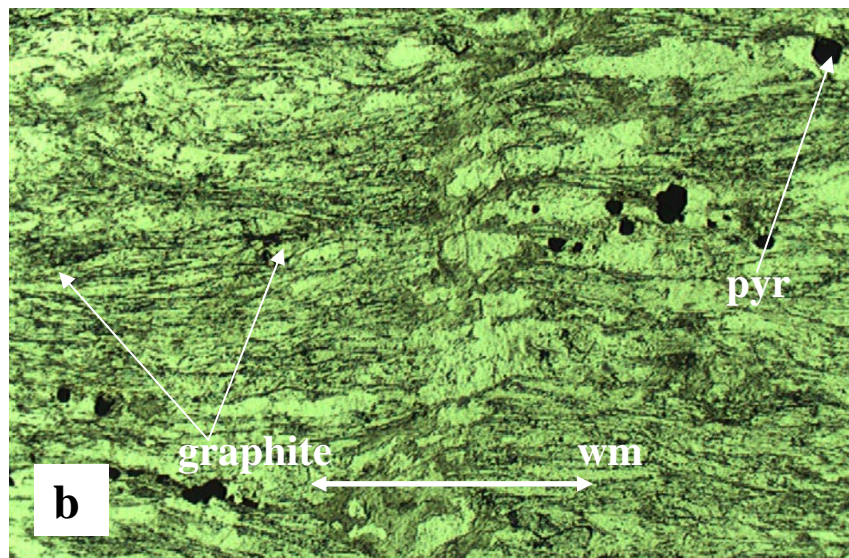
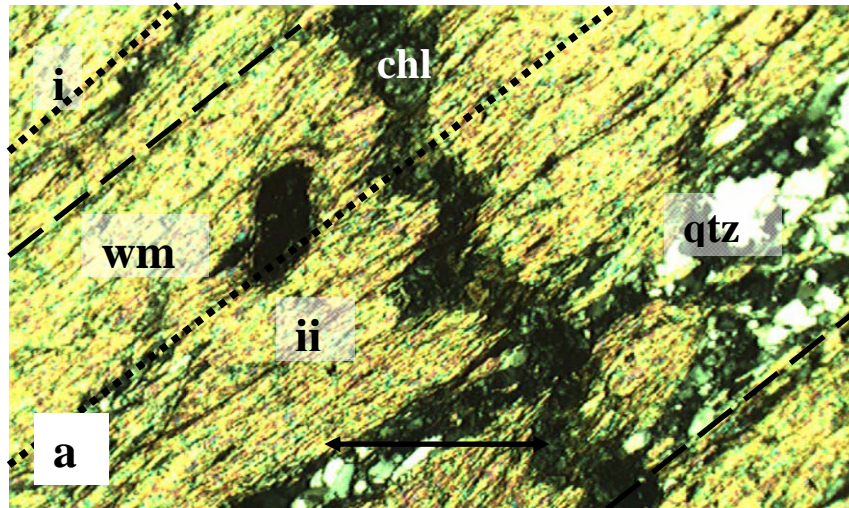


Figure 16. White mica and its occurrence the Brevard phyllonite. (a) Photomicro-graph of lepidioblastic white mica (wm) forming mica-preferred orientation foliation (i). This particular mica foliation (i) postdates quartzofeldspathic porphyroclasts (qtz), but is crosscut by a chlorite (chl) filled vein (ii). The photomicrograph was taken under cross-polarized light; bar = 1.0 mm. (b) Matrix of white mica displaying strongly developed mica-preferred orientation foliation, with extremely fine- grained graphite (as determined by reflected-light) occupying mica grain boundaries. Upper right corner is hexagonal pyrite (pyr) that replaces quartz. Photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (c) Mica fish porphyroclast comprised of white mica. Two foliations are shown; one forms the S-surface and the other forms the C-surface. The photomicrograph was taken under plane-polarized light; bar = 0.5 mm.



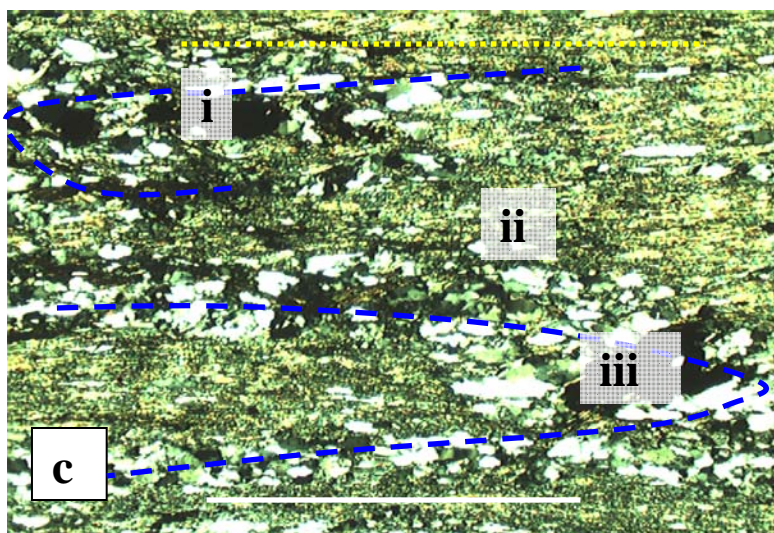
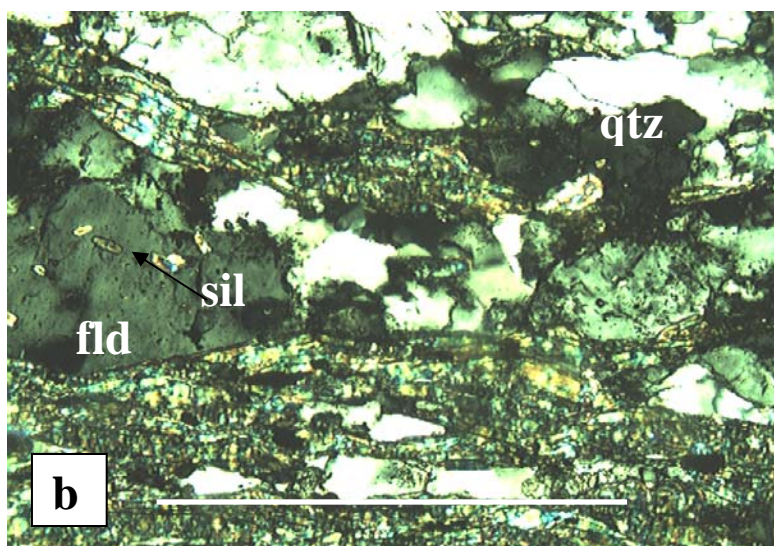
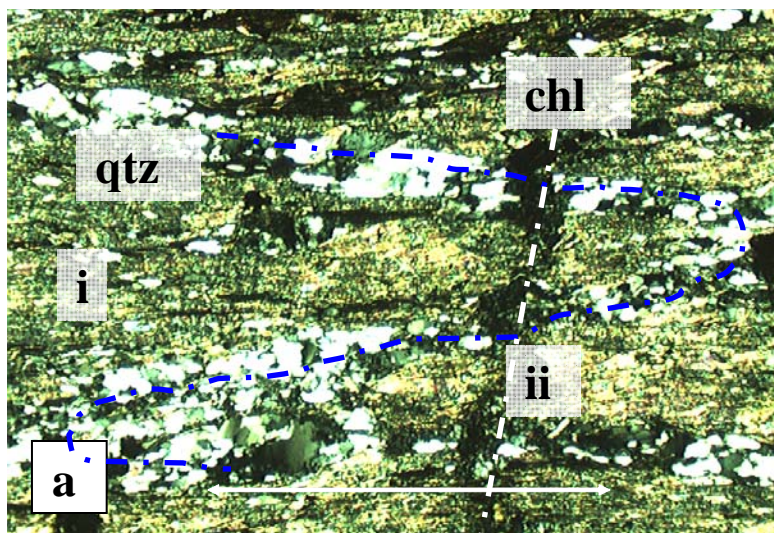
finely-crystalline (0.02 to 0.30 mm), xenotopic, equigranular, and elongated. Chlorite is green in color, and occurs as fine, lepidoblastic grains that are intercalated with white mica and quartz. It also tends to occur near localized zones of high strain. Graphite, as identified by oblique reflected light, is present as very finely-crystalline, equigranular (<0.01mm) xenotopic opaque granules. Graphite is observed along white mica grain boundaries within the matrix (Figure 16b). No biotite has been observed within the matrix of the Brevard phyllonite.

The Brevard phyllonite contains porphyroclasts that vary in mineralogy, size, and shape. These porphyroclasts contain mineral assemblages that are generally different from those of the previously described matrix. Many of these minerals have originated from rocks that sustained amphibolite facies metamorphism. Some of the porphyroclasts, such as mica fish, are the products of later greenschist facies metamorphism. Lepidoblastic grains of white mica, stacked oblique to the schistosity form 'mica fish'. The mica fish vary in size, and may be monocrystalline to polycrystalline. The mica fish display an internal mica-preferred orientation that is oblique to the foliation of the encompassing matrix (Figure 16c).

Elongated quartzofeldspathic porphyroclasts contain quartz, white mica, biotite, and feldspar. The white mica are loosely arranged into a mica-preferred orientation that is oriented oblique to encompassing matrix by 18° to 33°. Quartz grains adjacent to the white mica are anhedral, finely-crystalline and generally display interlobate and polygonal grain boundaries (Figure 17a). Quartz also forms recrystallized mortar structures around feldspar porphyroclasts, as well as monomineralic porphyroclastic tails and ribbons (Figure 17b). The quartz ribbons are commonly sheared out axial planar to isoclinal folding (Figure 17c).

Biotite is sparsely scattered within the interiors of quartz and white mica-rich porphyroclasts. Within these domains, biotite is present as discrete, extremely fine to finely-

Figure 17. Quartz and its occurrence in porphyroclastic domains within the Brevard phyllonite. (a) Quartz (qtz) grains within folded elongate ribbon-shaped porphyroclasts (blue dashed line) in phyllonite. A mica-preferred orientation foliation crystallized axial planar to the isoclinally folded quartz domain (i). This is in turn crosscut by a chlorite (chl) filled vein (ii). Photomicrograph was taken under crossed polarized light; bar = 1.0 mm. (b) Quartzofeldspathic porphyroclast containing xenotopic quartz grains and feldspar core. The feldspar (fld) contains sillimanite (sil) inclusions. Photomicrograph was taken under crossed polarized light; bar = 0.5 mm. (c) Quartz ribbon (i) displaying isoclinal folding (blue dashed line) and an axial planar mica-preferred orientation foliation (ii) within the phyllonite matrix. Late-stage pyritohedrons (iii) appear to selectively replace quartz grains. Photomicrograph was taken under crossed polarized light; bar = 1.0 mm.



crystalline (0.05 to 0.07mm) lathe-like grains lying adjacent to the grain boundaries of polygonal quartz (Figure 18a). Biotite lathes display two mica preferred orientation foliations, one oriented parallel to continuous schistosity of the matrix, the other having an oblique angle of 43° to 53°. Chlorite alteration is pervasive and occurs along biotite grain boundaries (Figure 18b).

Microcline feldspar is fine (0.10 to 0.15 mm) to medium (0.25 to 0.50 mm) crystalline, anhedral and displays faded tartan twinning. It generally occupies the cores of asymmetric, rotated porphyroclasts (Figure 19a). The microcline grains exclusively contain inclusions of sillimanite (Figure 19b). Coarsely-crystalline (0.4 to 0.5 mm) plagioclase displays albite twinning (Figure 19c) and forms elongated quartzofeldspathic porphyroclasts in association with white mica and quartz. Both feldspars display varying degrees of sericitization and microfractures.

Sillimanite occurs as finely crystalline, subidiotropic, rod-shaped inclusions within microcline (Figure 19b). The grains are colorless, randomly oriented and uniform in grain size.

Monocrystalline and polycrystalline cordierite porphyroclasts occur in trace amounts within the phyllonite (Figures 20a-b). The cordierite grains are xenotopic, medium- to coarsely-crystalline (0.10 to 0.50 mm), and contain inclusions of quartz or white mica (Figures 20a-b). The quartz inclusions are usually randomly oriented, however, the white mica may display a weak mica preferred orientation foliation.

Dolomite porphyroclasts are composed of finely-crystalline (0.05 to 0.10 mm), xenotopic dolomite, which is mantled by finely-crystalline quartz and lepidoblastic white mica (Figure 21). These porphyroclasts were observed in samples of phyllonite taken from the footwall of the fault-line scarp.

Figure 18. Biotite and its occurrence in porphyroclastic domains within the Brevard phyllonite. (a) Finely-crystalline biotite and white mica in a ribbon-shaped porphyroclastic (i) domain within the Brevard phyllonite. Biotite is finer-grained than the white mica and may display partial alteration to chlorite. The ribbon-like structure appears to be isoclinally folded, and then subjected to stacking along discrete shear-band surfaces (ii). Photomicrograph was taken under crossed polarized light; bar = 1.0 mm. (b) Fine-grained biotite (bio) displaying partial alteration to chlorite (chl) in center of grain. Photomicrograph was taken under plane polarized light; bar = 0.5 mm.

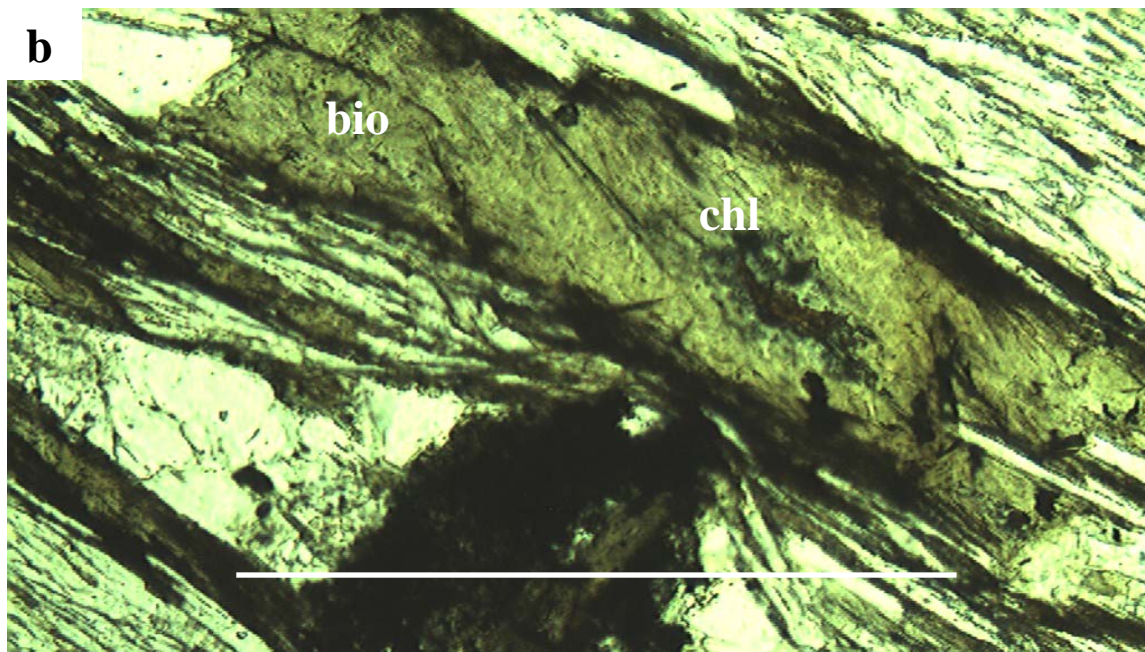
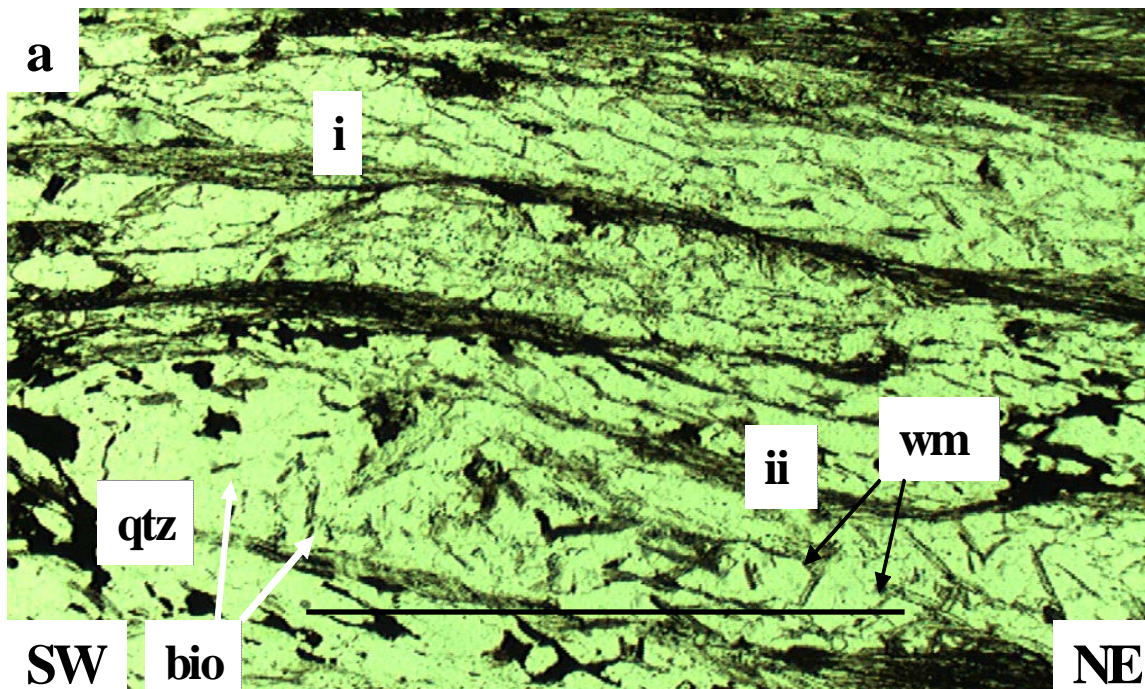


Figure 19. Sillimanite-bearing microcline and plagioclase feldspar porphyroclasts within the Brevard phyllonite. (a) Porphyroclast cored by microcline feldspar (kspar) displaying a weak tartan-pattern twinning. Photomicrograph was taken under cross-polarized light; bar = 0.5 mm. (b) Sillimanite (sil) inclusions within a potassium feldspar porphyroclast (kspar). The photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (c) Porphyroclast (i) containing a plagioclase (alb) feldspar core. The plagioclase grain displays albite twinning, and contains inclusions of white mica (wm). The photomicrograph was taken under cross-polarized light; bar = 0.5 mm.

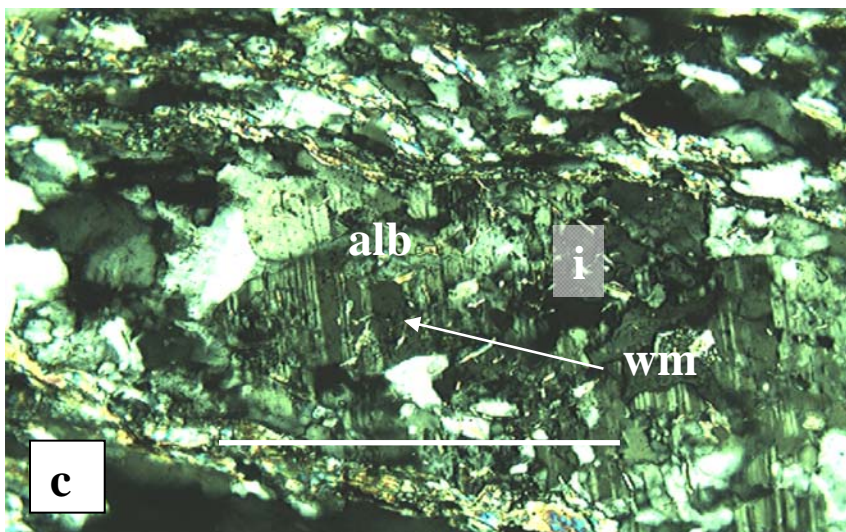
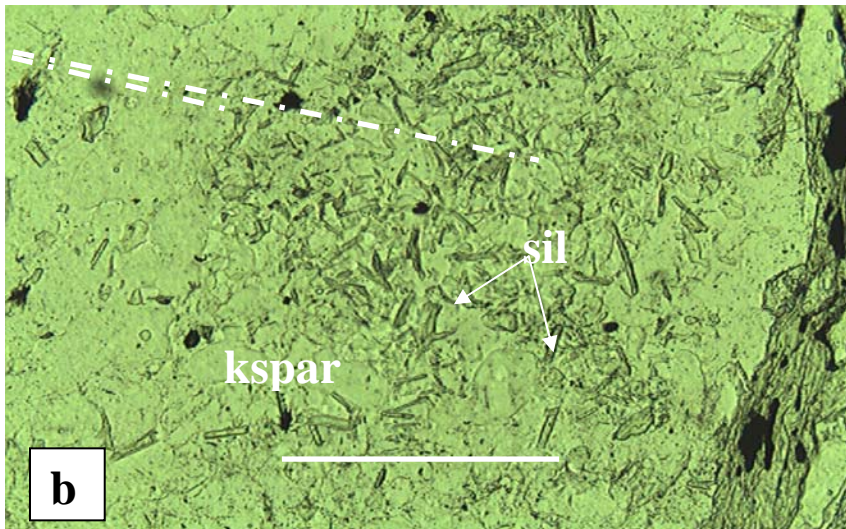
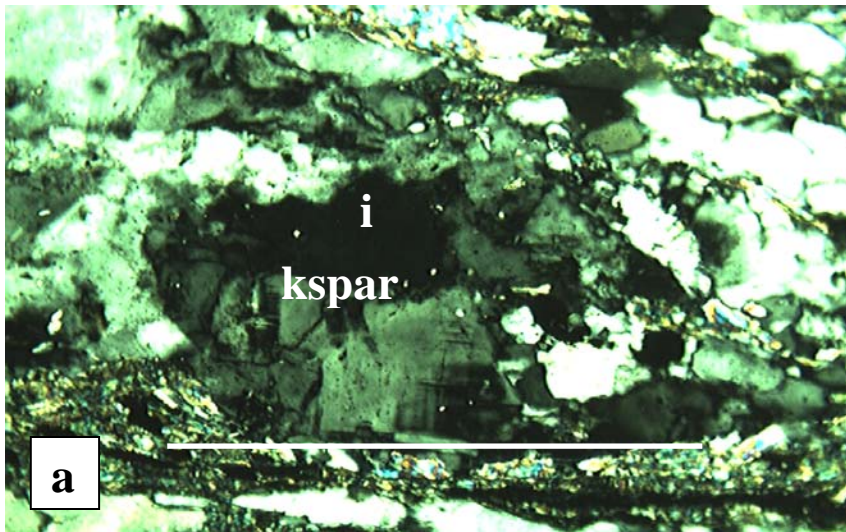
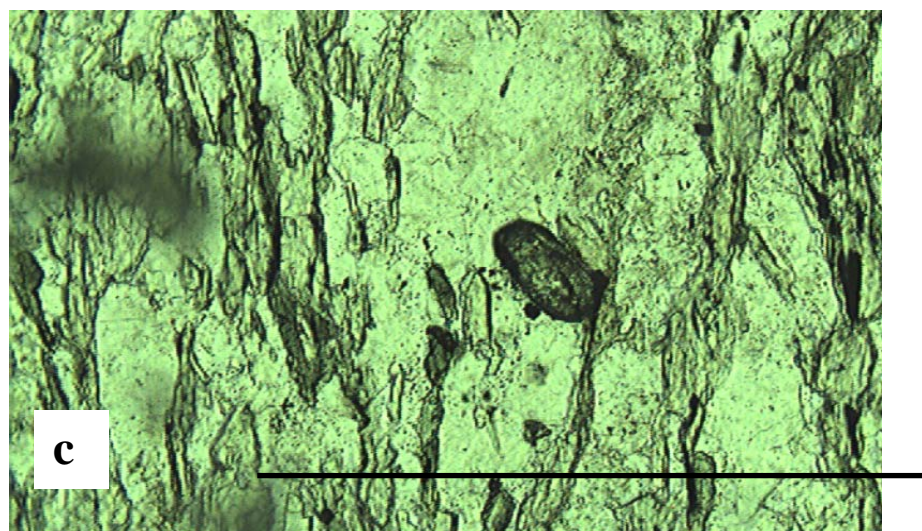
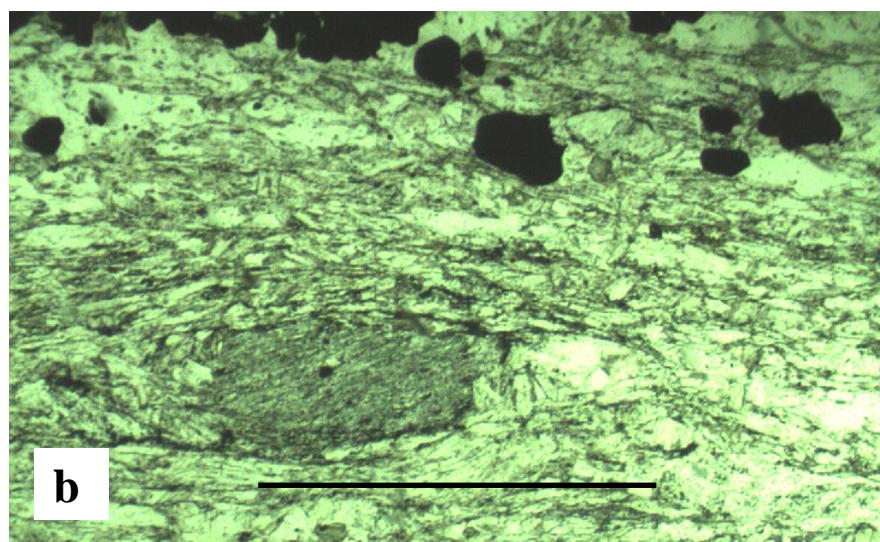
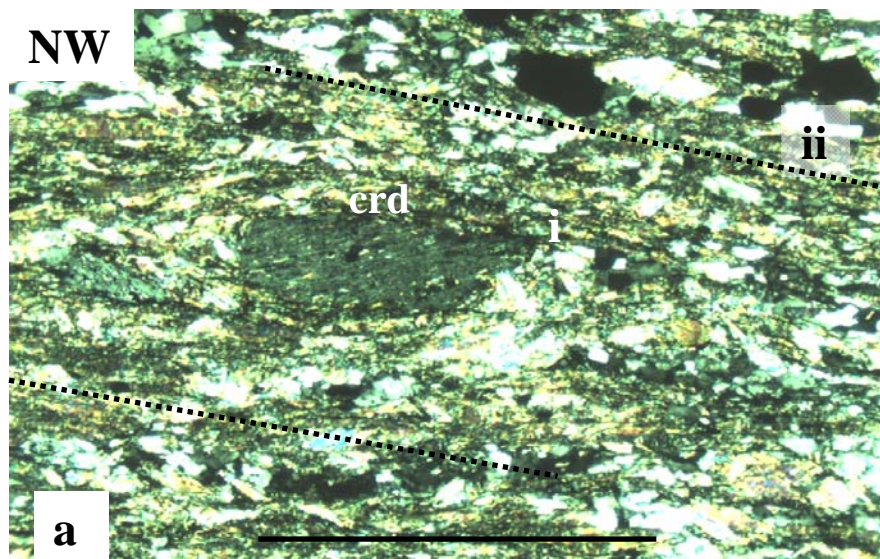


Figure 20. Cordierite porphyroclasts and zircon grains within the Brevard phyllonite. (a) Porphyroclast of cordierite (crd) containing (i) white mica inclusions that display an early mica-preferred orientation foliation. Cordierite porphyroclast is crosscut by the white mica-rich matrix (ii) of the phyllonite. Upper right hand corner are euhedral pyrite. Photomicrograph was taken under cross-polarized light; bar = 1.0 mm. (b) Photomicrograph of the same cordierite porphyroclast under plane-polarized light. Later-stage mineralization of euhedral pyrite appears to replace quartz, located above cordierite porphyroclast. Photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (c) Zircon grain (zir) within a quartz and white mica-rich domain. Photomicrograph was taken under plane-polarized light; bar = 0.5 mm.



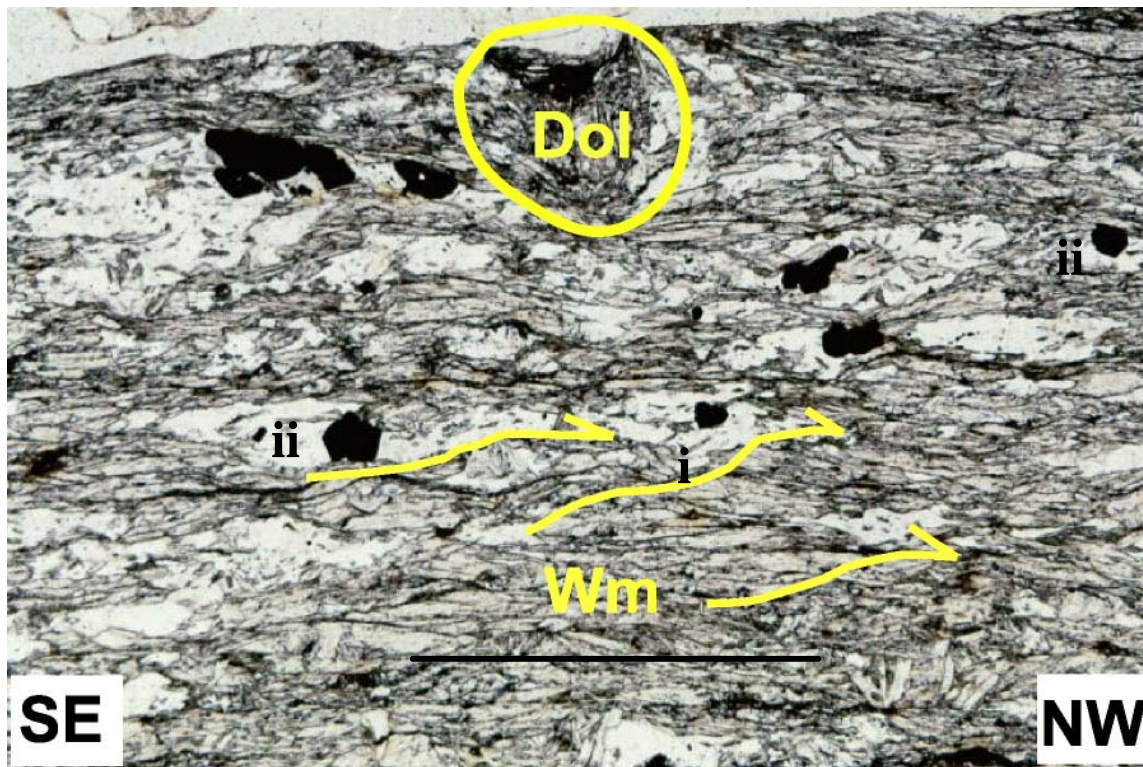


Figure 21. Dolomite porphyroblast within the Brevard phyllonite. (a) A porphyroblast of dolomite (dol) was found within a thin section that was cut perpendicular to strike. Mica fish (i) display tops to the northwest. Note presence of euhedral pyrite (ii). Sample was collected along the surface of the footwall of the fault-line scarp, north side of quarry. Photomicrograph was taken under plane-polarized light; bar = 1.0 mm.

Zircon is present as high relief, pale green, fine to coarse (0.05 to 0.20 mm) euhedral to subhedral grains (Figure 20c). Zircon occurs as occasional individual grains throughout the white mica rich matrix.

Limonite pseudomorphs after garnet occur in several hand samples. These are rounded grains, 1.0 to 4.0 mm in diameter, and are wrapped by white mica.

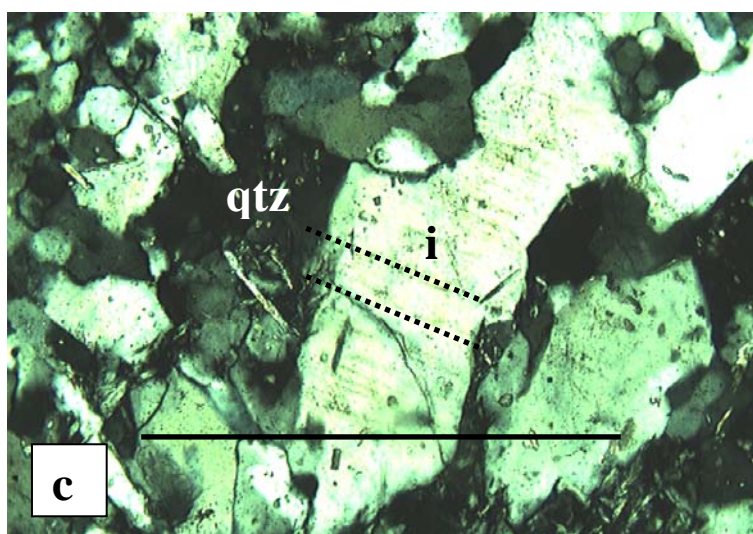
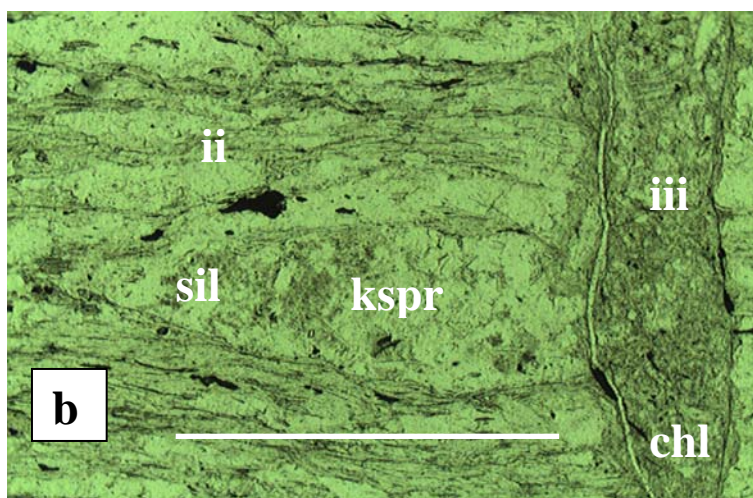
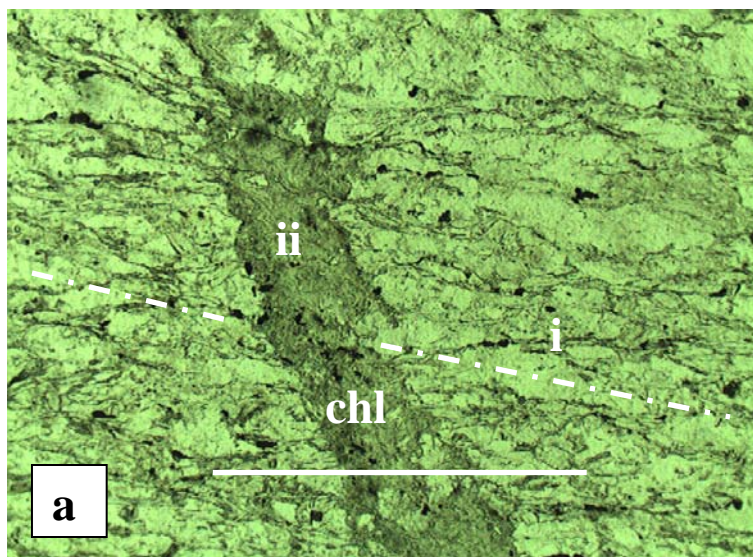
Veinlets crosscut the Brevard phyllonite (Figure 22a-b), measure 0.10 to 0.5 mm wide and generally contain varying amounts of chlorite and quartz. The chlorite is finely-crystalline, non-pleochroic, lepidoblastic, and is mineralized oblique (45° to 90°) to the vein wall in close association with xenotopic quartz (Figure 22a-b). Where no quartz is present, the chlorite sheets lie parallel to the vein wall. Quartz grains are generally xenotopic, medium grained, and have a seriate-interlobate grain shape. The quartz grains display intracrystalline deformation lamellae and sub-grain development (Figure 22c) where it is crystallized normal to the vein walls.

Late-stage mineralization associated with brittle deformation primarily occurs along fracture surfaces. Non-pleochroic chlorite, similar to vein-filling chlorite, is observed to be oriented with its basal cleavage parallel to the fracture surface. Fractures also contain sparry calcite that displays type-I twinning. The calcite spar is associated with chlorite and the polygonal quartz as a recrystallized vein-filling material.

Pyrite is present as a post-tectonic, late-stage quartz replacement mineralization. Pyrite is fine- to medium-crystalline and forms idiotopic to subidiotopic pyritohedrons (Figures 16b, 17c, 20b and 21).

Cobble- to block-size clasts entrained within the Brevard phyllonite contain unique mineralogical and textural characteristics and are considered to be 'exotic rocks' in the sense of

Figure 22. Vein-filling mineralization within the Brevard phyllonite. (a) Chlorite vein (ii) that crosscuts the white mica-rich matrix (i). Photomicrograph taken under plane-polarized light; bar = 1.0 mm. (b) Chlorite-filled vein (iii) crosscutting a feldspar porphyroclast (i) and the white mica-rich matrix (ii). The porphyroclast (i) contains microcline with inclusions of sillimanite (sil). Photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (c) Anhedral quartz grain within a chlorite and quartz-filled vein. Lamellae structures (i) are present on several grains. Photomicrograph was taken under cross-polarized light; bar = 0.5 mm.



Hatcher (1971). These rocks are derived from higher-grade Blue Ridge affinity rocks and are considered separately from the Brevard phyllonite.

Textural Features

The Brevard phyllonite inherits its texture from a complex deformational history. Many of the textural features of the lithodeme are products of early ductile deformation such as the matrix, porphyroclasts and exotic rocks. Later stage veining, jointing, and fracturing are present as crosscutting features.

The matrix of the Brevard phyllonite is composed of fine- to medium-crystalline white mica that displays a well-developed, mica-preferred orientation (Figures 23a-c). In thin section, the matrix and associated mica fish are transected by millimeter-scale shear zones. These minor shear zones are generally lie parallel to the mica-preferred orientation of the matrix, collectively forming a pervasive shear band cleavage. Therefore, it is the shear band cleavage that gives the phyllonite its characteristic schistosity (Figures 15a-b, 24a). Contained within the matrix are features such as micaceous porphyroclasts (Figure 23b), mica fish (Figures 16c, 24b), quartzofeldspathic porphyroclasts and ribbon structures, and mono-crystalline porphyroclasts.

Micaceous porphyroclasts vary between 1.0 to 7.0 mm in length and are bounded by shear bands within the matrix (Figure 23b, 24b). The porphyroclasts are composed of medium- to coarsely-crystalline (0.1 to 1.0 mm) white mica. Mica fish (0.4 to 1.0 mm) are commonly found adjacent to and along the trailing edges of these porphyroclasts. The mica fish are losenge-shaped grains of lepidoblastic mica that range in size from 0.20 to 1.5 mm (Figures 16c, 23b, 24b).

Figure 23. Matrix microtextures within the Brevard phyllonite. (a) Thin section showing the microtexture of a matrix dominant phyllonite where proportion of porphyroclasts to matrix is roughly equal. Note that there are very few structures present within the matrix and that the S-surface of the mica is nearly parallel to the C-surface shear bands. This feature is the result of significant amounts strain and dynamic recrystallization. Photomicrograph taken under cross-polarized light; bar = 1.0 mm. (b) Elongated polycrystalline micaceous porphyroclasts and mica fish. The porphyroclasts are bounded by shear bands. Photomicrograph was taken under plane-polarized light; bar = 1.0 mm. (c) Photomicrograph of microscale shear-band cleavage in coarsely-crystalline phyllonite. The shear-band cleavage produces the button-like schistosity in hand sample. Photomicrograph was taken under cross-polarized light; bar = 1.0 mm.

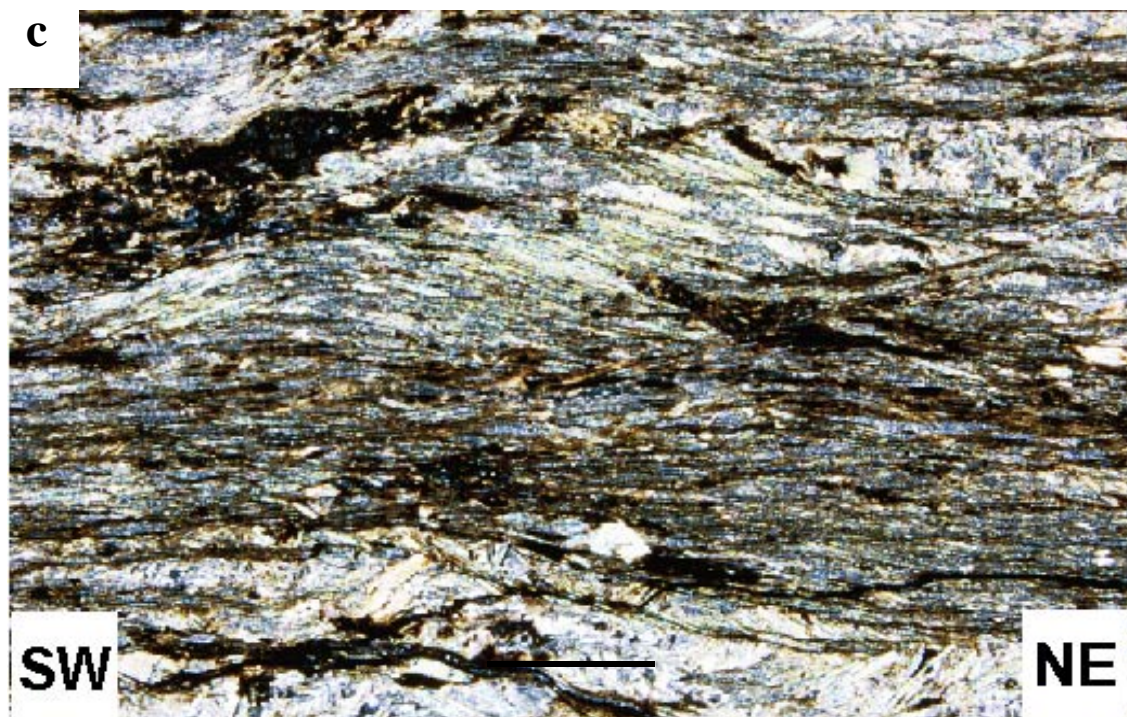
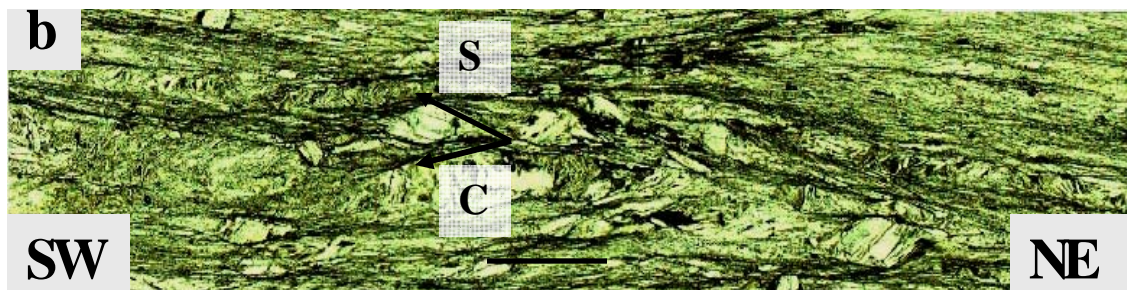
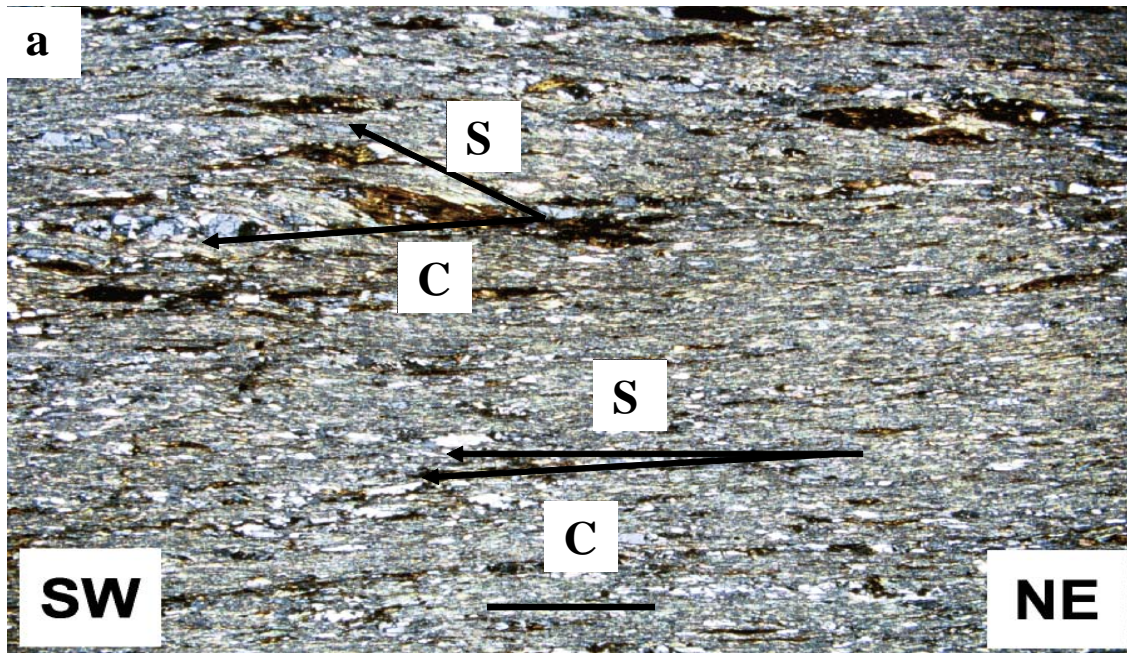
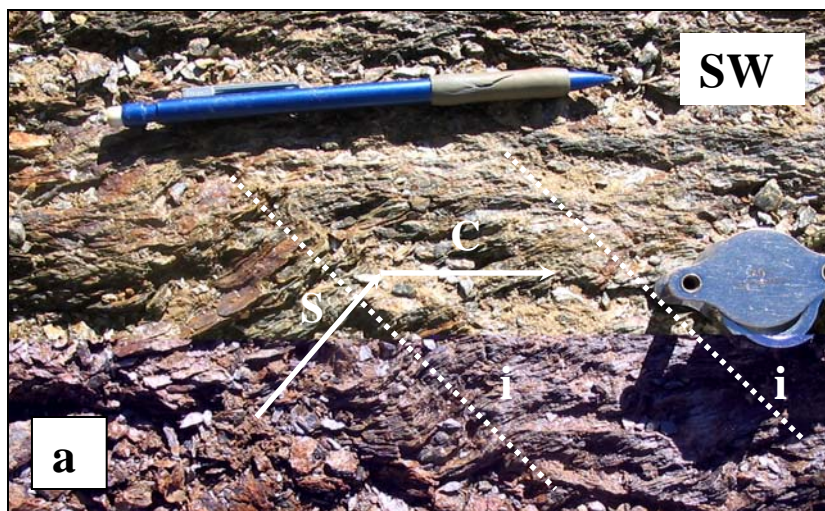


Figure 24. Mica fish and shear-band cleavage within the Brevard phyllonite.

(a) Photograph of the Brevard phyllonite with well-developed schistosity. The schistosity is formed from the microscale development of shear band cleavage. Mica fish within the phyllonite display upward ramping to NW and SW shear sense within the lithodeme. Here, the pencil tip indicates tops direction to the SW. S and C surfaces given for reference. Note the presence of a weak outcrop-scale crenulation cleavage (i). (b) Photomicrograph of S and C surfaces within white mica fish. The S-surface is a mica-preferred orientation foliation, while the C-surface is a shear-band. The ramping fabric displays tops to SW shear sense. Photomicrograph was taken under plane polarized light; bar = 0.5 mm. (c) Photomicrograph of the crenulation cleavage along spaced fold axes (i) that are verging NW. Photomicrograph taken under plane-polarized light; bar = 1.0 mm.



Mica fish display tops to west orientation (Figure 24a-b). They have internal cleavage development, or mica-preferred orientation foliation that is commonly oblique to the encompassing foliation of the phyllonite (Figures 16c, 23b, c, 24a and b). The deformation mechanisms associated with their development include; slip, rigid body rotation, boudinage and recrystallization (Passchier and Trouw, 1998, p.123).

Quartzitic porphyroclasts are comprised chiefly of quartz and white mica, with lesser amounts of biotite, cordierite, microcline and plagioclase feldspars. The quartz-rich porphyroclasts are extremely elongated and ribbon-shaped (Figures 17a, c, and 18a). They have been measured to have maximum lengths of 10.0 to 28.0 mm in length from thin sections cut in the direction of strike. The mica grains contained within these porphyroclasts display a shape-preferred orientation that is oblique to the shear band cleavage of the matrix (Figure 18a). Biotite generally has two orientations; one that is 43° to 53° and a second that is parallel the shear band cleavage. Microcline and plagioclase containing sillimanite inclusions occur within ribbon-shaped porphyroclasts, and smaller δ -type porphyroclasts (Figures 19a-c). Plagioclase and microcline feldspar form the cores of these smaller (1.0 to 2.0 mm) asymmetric porphyroclasts (Figures 19a-b) and display varying degrees of dextral rotation to the southwest. Both feldspars display varying amounts of sericitization; some rotated cores are completely sericitized. Isoclinal folds fold some of the ribbon shaped quartzitic porphyroclasts (Figure 17c). The limbs of these folds may be crosscut by shear bands (Figure 17a and c, 18a).

Monocrystalline porphyroclasts such as zircon, cordierite and dolomite are disseminated throughout the matrix of the phyllonite. Cordierite is anhedral, (Figures 20a and b), wrapped by white mica, but displays little in the sense of rotation. Zircon occurs within matrix as subhedral detrital grains (Figure 20c). Xenotopic dolomite, wrapped by white mica occurs within the

matrix of Brevard phyllonite (Figure 21). Dolomite forms the core of a porphyroclast that was observed within phyllonite sampled adjacent to the footwall of the fault-line scarp.

Exotic rocks

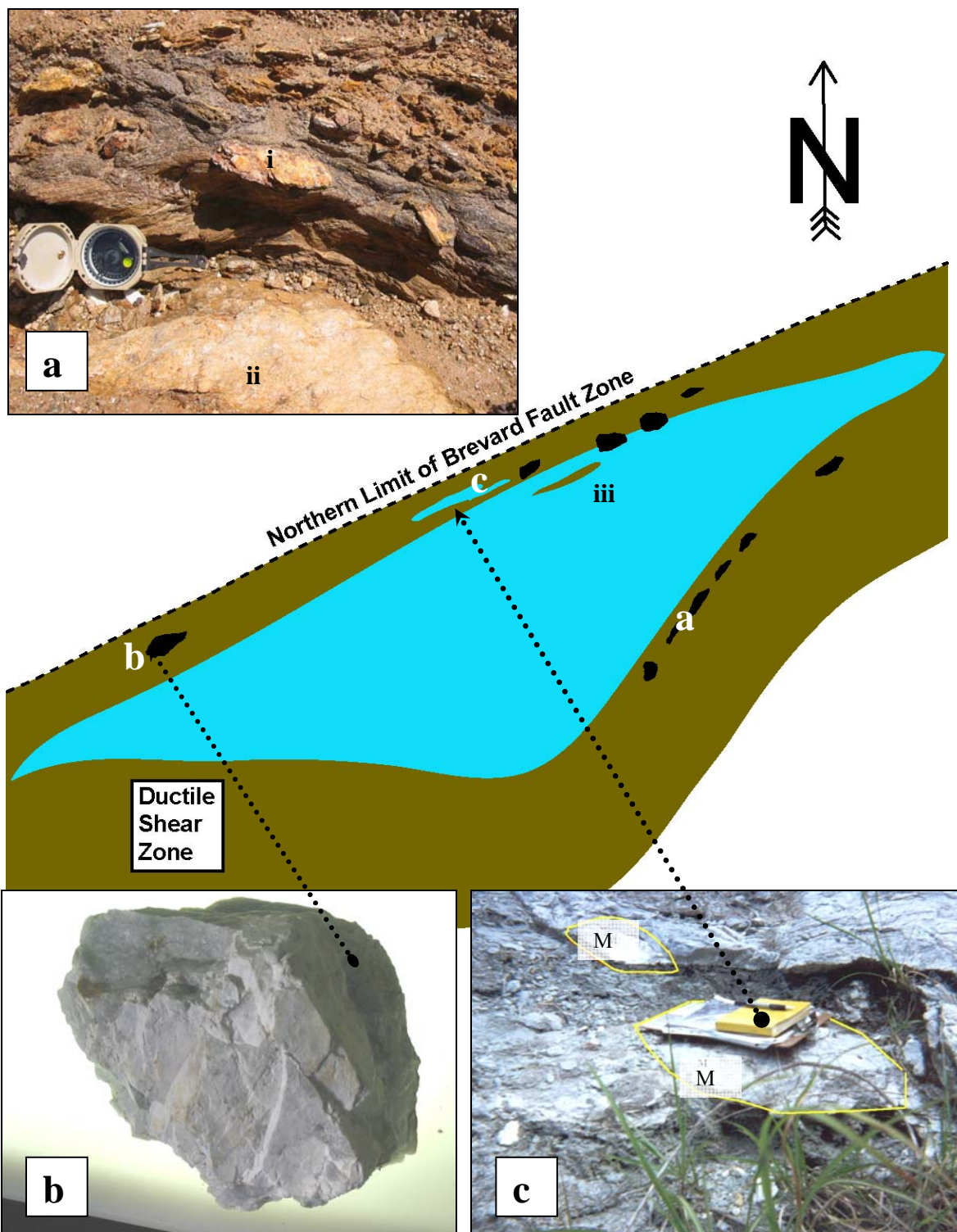
Exotic rocks that were described by Hatcher (1971) are entrained within the Brevard phyllonite. Blocks that have been identified thus far include cobble- to block-sized clasts of pegmatite, marble, staurolite schist and garnet-idocrase-bearing schist. Many of these rocks are saprolitic or display some degree of weathering. These rocks are overprinted by later brittle fractures and joints.

One outcrop containing exotic block lithologies is located near an unimproved roadbed adjacent to the southeastern head wall of the boundary fault. The rock is a saprolitic quartzofeldspathic rock that contains rotated slabby-pieces of schist and coarse-grained quartz (Figure 25a). These rocks are entrained within a matrix of fine-grained, saprolitic, graphitic phyllonite that is crosscut by localized isoclinal folding. The graphitic phyllonite displays an undetermined amount of rotation. The sizes of the rocks vary from 5 to 15 cm in diameter and they contain schistose foliation. The rock is highly saprolitic and is easily weathered.

A cobble-sized clast of pegmatite was recovered from the southwestern side of the quarry, adjacent to the fault-line scarp between the Fletcher marble and the Brevard phyllonite. The pegmatite is composed of medium-crystalline quartz and coarse-extremely coarse grained microcline (Figure 25b).

Carbonate clasts displaying a white mica preferred orientation foliation are entrained within a zone of phyllonite that lies structurally below the northern fault-line scarp (Figure 25c). The clasts are lensoidal slabs of marble, 15.0 cm wide by 30.0 cm long that pinch out into

Figure 25. Diagram showing the relative locations of exotic rocks entrained within the Brevard phyllonite in the study area. Brittle faulting is not shown. (a) Outcrop of schist (i) and feldspathic rock (ii) that are entrained within saprolitic graphitic phyllonite. Brunton pocket transit compass used for scale. Slice of phyllite referenced by Dabbagh (1975, 1981) shown center diagram (iii). (b) Sample of sheared pegmatite from the western side of the quarry, taken from the Brevard phyllonite. (c) Cobble-sized clasts of marble (M) entrained within phyllonite, lying structurally below the northern fault-line scarp. Clipboard (0.3 meter long) is atop the marble outcrop for scale.



chlorite and graphitic-rich phyllonite. Dabbagh (1975, 1981) observed a similar relationship within the marble. He described the presence of ‘thinly-layered sericite phyllite’ within the Fletcher marble adjacent to the footwall of the fault- line scarp.

Two exotic rocks containing higher-grade mineral assemblages are also found within the lithodeme. A cobble-sized block of staurolite schist was collected from exposures of phyllonite along the southeast side of the study area. The schist is silver-brown in color, and contains extremely coarse-grained staurolite porphyroblasts, within a fine-grained schistose matrix of white mica and quartz. In thin section, the rock contains a chlorite-white mica-quartz rich schistose foliation that is truncated by porphyroblasts of staurolite (Figure 26a). The mineralogy and textural features of this rock is indicative of dynamic crystallization under amphibolite facies conditions. The second block is idocrase-bearing, garnet mica schist. In thin section, it has a mineralogy consisting of quartz, chlorite, sericite after kyanite, poikilitic garnet, opaque minerals and idocrase (Figure 26b and c). The idocrase occurs as finely-crystalline, subhedral grains within the matrix.

Brittle features

Fractures and joints crosscut all textural and mineralogical features within the Brevard phyllonite (Figures 15 and 27). The joints are hairline fractures, having partings that range from 0.7 to 1.8 mm. Random fractures crosscut the joints and are filled with fine sparry calcite, chlorite, or may be open.

Figure 26. Relict high-grade mineralogy within selected exotic rocks. (a) Photomicrograph of staurolite white mica schist. Staurolite porphyroblasts (sta) crosscut the white mica-dominated foliation (wm). The sample contains a mica-preferred orientation foliation that represents the earliest recognized foliation within the study area. Contained within the foliation are sericitized kyanite pseudomorphs (ky). Photomicrograph taken under plane-polarized light; bar = 1.0 mm. (b) Photomicrograph of a sericitized garnet (gnt) mica schist taken from an exotic rock. Photomicrograph taken under plane-polarized light; bar = 1.0 mm. (c) Idocrase crystal. Photomicrograph taken under cross-polarized light; bar = 0.25 mm.

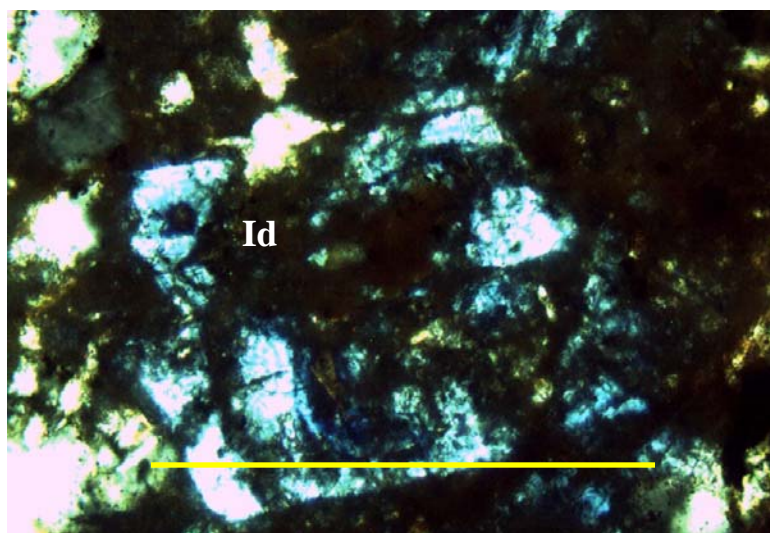
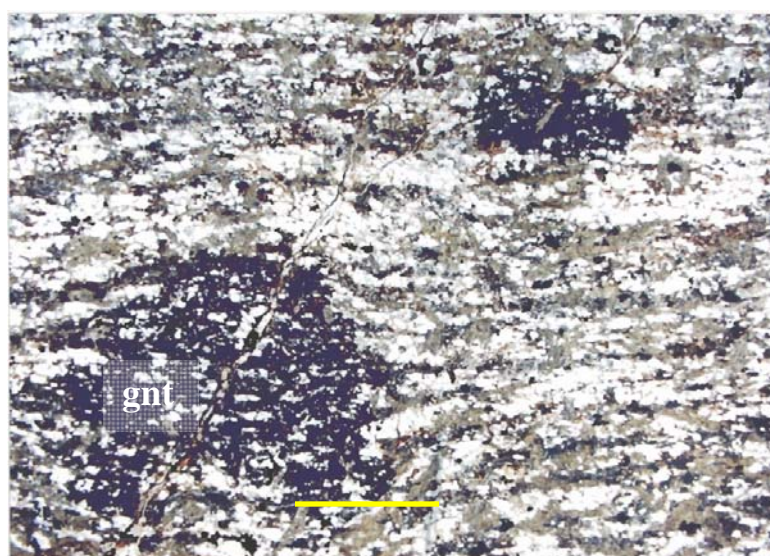
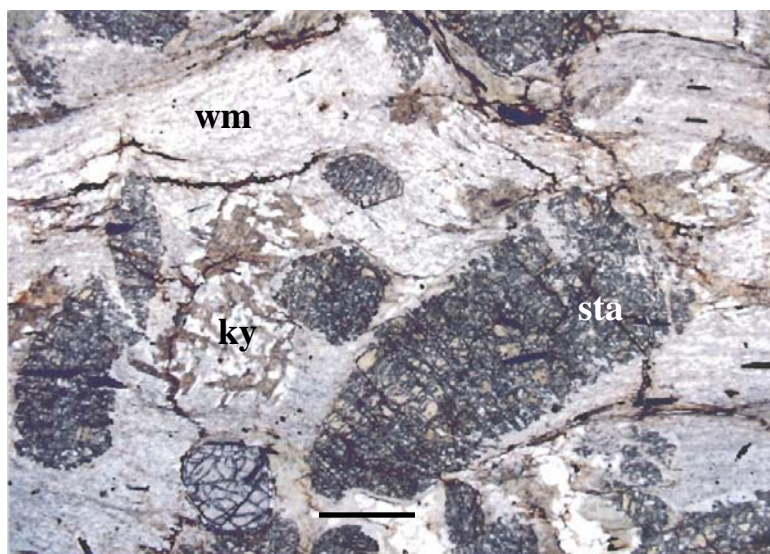


Figure 27. Fractures within the Brevard phyllonite. (a) Mesoscale fracturing in an outcrop of fine-grained phyllonite. Rock hammer is for scale (0.3 meters). (b) Thin section cut normal to strike, parallel to the dip of the foliation. The thin section contains a repetitive series of discrete fractures containing no mineralization. Photomicrograph was taken under cross polarized light; bar = 1.0 mm.



STRUCTURAL ELEMENTS

Planar Structures

Continuous schistosity of the Brevard phyllonite

The Brevard phyllonite has a well-developed continuous schistosity that is easily recognizable and measurable in outcrop (Plate 1, Figure 24a). Its appearance is aesthetically enhanced by the characteristic button-like texture, inherited from mica-fish development (Figure 15b, 23b, 24a and b). The schistose foliation has an average planar orientation that strikes N 25° E, and dips 54° to the southeast (Figure 28).

The schistosity of the Brevard phyllonite can also be related to the S-C mylonite terminology of Lister and Snoke (1984), in which the Brevard phyllonite would be classified as a type-II S-C mylonite. In the terms of Lister and Snoke (1984), the shear bands form the C-planes, while the basal cleavage of the mica grains form the S-planes. In thin section, the older S-planes are inclined to the younger C-planes by a 33 to 50 degree angle. For the purpose of clarity, the term shear band cleavage will be used to describe S-C mylonite fabric herein, unless there is a reasonable need to describe particular S-C fabric elements.

Fletcher marble shape fabric and lattice preferred orientation foliation

Crystal-plastic deformation of the Fletcher marble produced the grain-shape fabric indicative of a mylonite (Figures 8a, 14a-d). This grain-shape fabric was produced by active crystal-plastic deformation mechanisms such as; grain boundary migration recrystallization, subgrain rotation recrystallization, and recovery. The grain shape fabric is best developed in mylonitic fine- to medium-grained domains. Talc and white mica grains are weakly aligned within the grain-shape fabric and they define a lattice-preferred orientation foliation. A

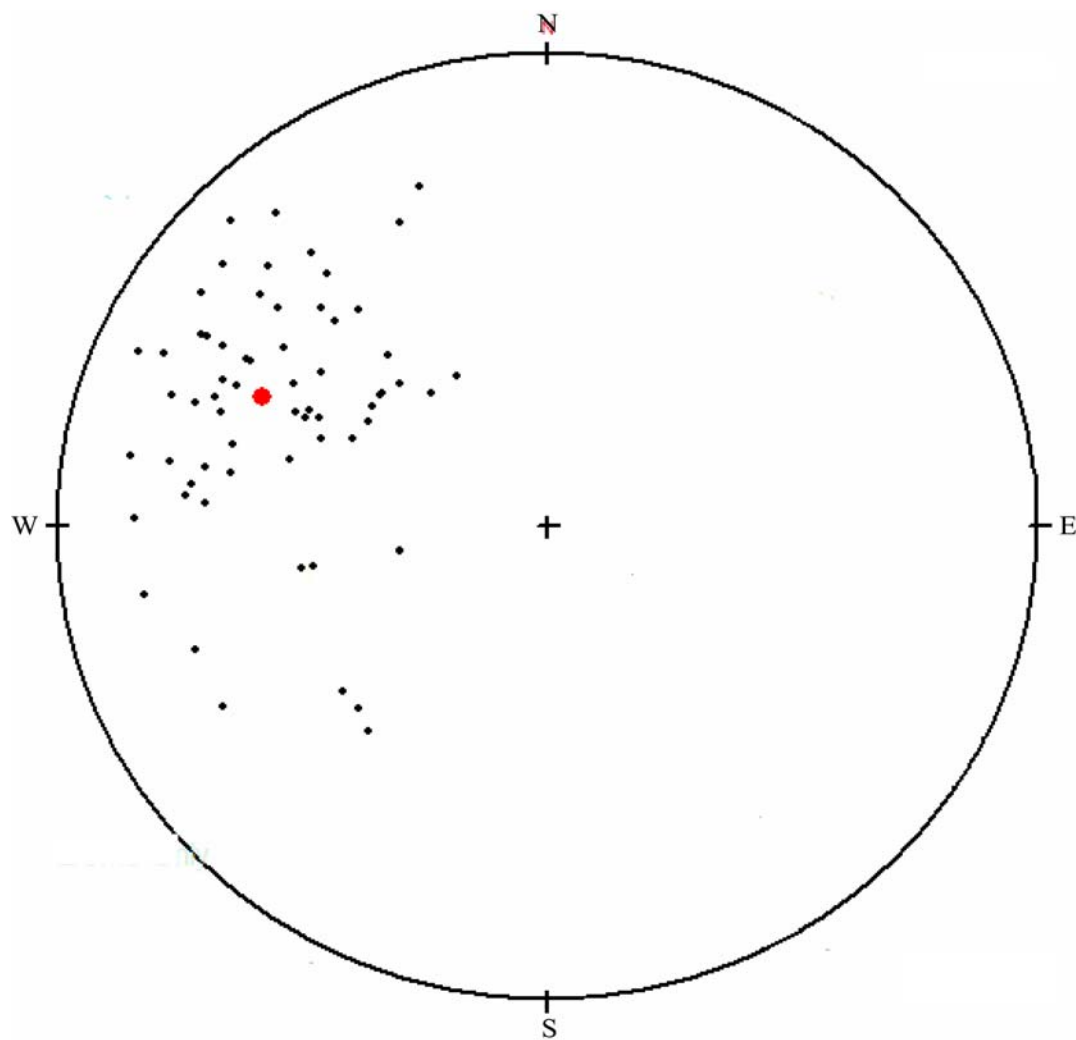


Figure 28. Stereogram of the schistose foliation within Brevard phyllonite. Poles to plane, equal area, lower hemisphere stereogram, N=70. Red dot is the average orientation of the schistose foliation; N 25° E, dipping 54° SE.

stereographic plot of dolomite c-axes orientations from a limited number of samples suggests that there is a lattice-preferred orientation in the marble (Figure 29).

Crenulation cleavage foliation

The crenulation cleavage foliation is a micro- to meso-scale feature that folds the schistosity in the Brevard phyllonite. In outcrop, the crenulation cleavage is difficult to recognize few were measured during the study. The crenulation cleavage planes that were measured have highly variable planar orientations that generally dip to the northwest at moderate to steep angles (Figure 30). Microtexturally, the crenulation cleavage consists of parallel sets of irregularly-spaced gentle to tight folds that fold the schistosity of the phyllonite (Figures 24c). The axial planes of these folds are inclined 30° to 40° to the shear band cleavage domains.

Color banding

Color banding that consists of unevenly spaced, blue colored, bands forms a penetrative planar feature within the Fletcher marble. The color bands are 0.50 mm to 15.0 cm thick and are intercalated with white marble. These intercalated domains span finite intervals up to 1.5 meters thick. The color banding has an average orientation that strikes N 12° E, and dips 57° to the southeast (Figure 31). It may display internal folding that produces open, isoclinal and sheath folds. The color banding is crosscut by stylolites, multiple joint sets, and faulting.

Joints and shear fractures

The Brevard phyllonite contains systematic joint sets that are best developed in the footwall of the fault-line scarp adjacent to the Fletcher marble. The jointing facilitates the parting

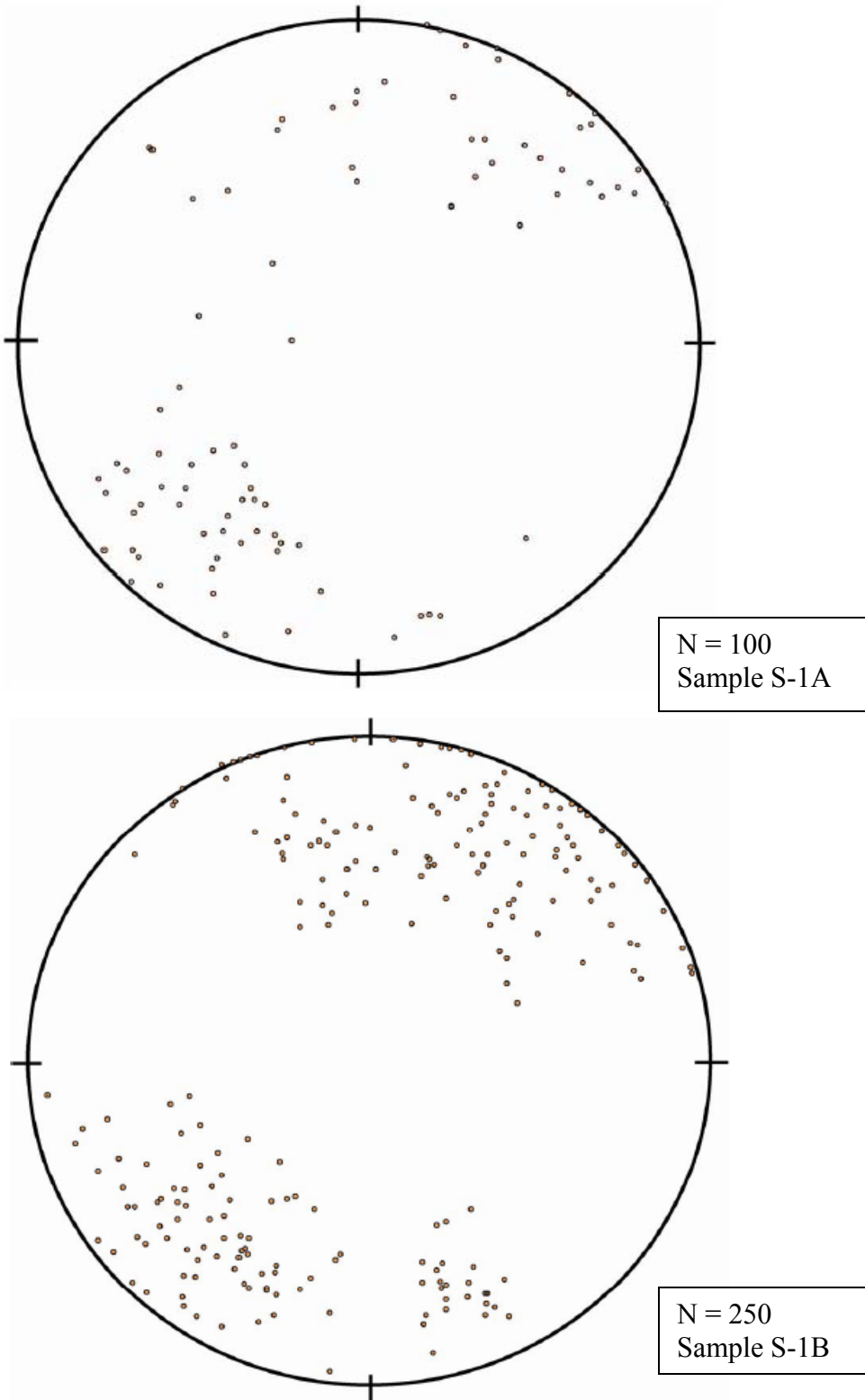


Figure 29. Lattice preferred orientation within the Fletcher marble. Equal area, lower hemisphere stereograms. Measurements of dolomite c-axes taken with a universal-stage, N = 100 and 250.

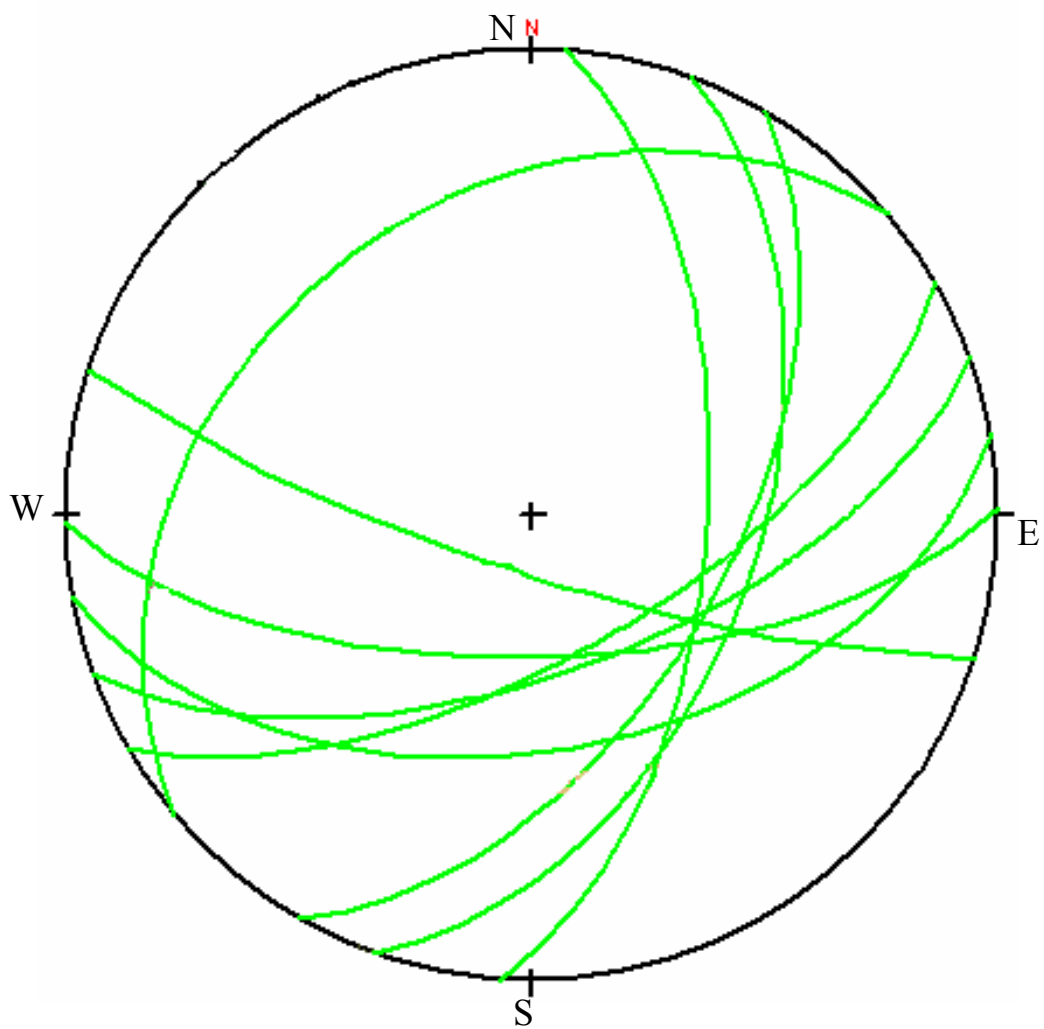


Figure 30. Stereogram of crenulation cleavage within the Brevard phyllonite. Equal area, lower hemisphere stereogram, N=9.

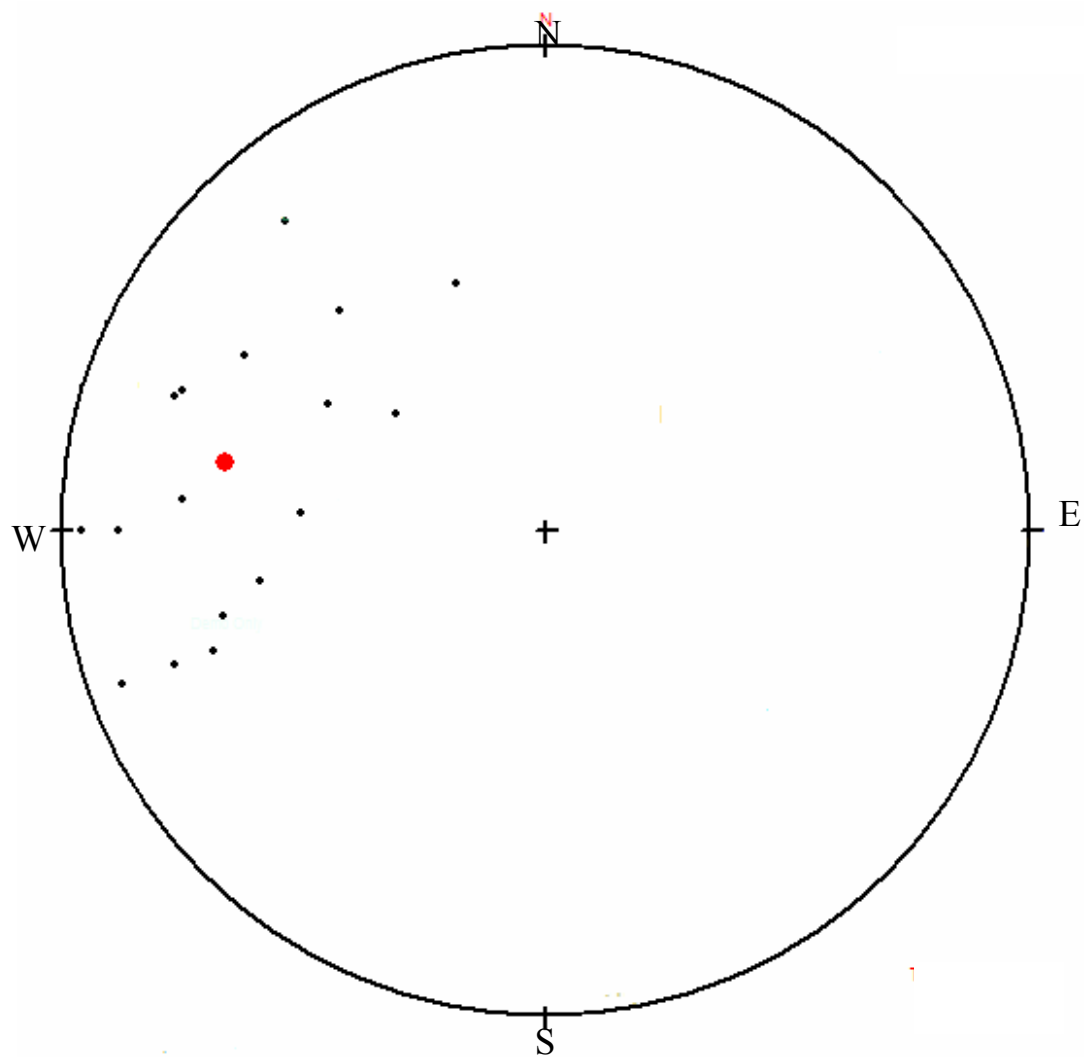


Figure 31. Stereogram of color banding within the Fletcher marble. (a) Equal area, poles to planes, lower hemisphere stereogram, N=19. The red dot represents the average planar orientation of the color banding; N° 12 E dipping 57° southeast.

of the phyllonite into platy (1 to 3 mm thick) to slab-shaped (>15 cm thick) partings. Jointing is usually tight and is stained by iron oxide. At least three unique joint sets are recognized from their trends in strike, shown in a Rose diagram (Figure 32a). The first joint set is has a strike that is N 33° E and mimics the trend of the Brevard fault zone. Two additional joint sets have strikes that trend N 39° E and N 77° E.

The Fletcher marble is also crosscut by multiple, systematic and non-systematic joint sets (Figure 32b). The joint planes are smooth and produce thin partings 0.5 cm in width and blocks 25.0 cm in width. Four joint sets have been recognized from a Rose diagram plotting the strike of the joints measured. The first joint set has a strike of N 42° E, which also mimics the trend of the Brevard fault zone. Three additional joint sets are recognized that have strike orientations measuring N 14° E, N 75° W, and S 69° E. The presence of jointing affects the economic value of the marble quarried. Extensive jointing limits the use of the marble for architectural stone, but it facilitates removal and processing required for ultra-fine powders mentioned in the Appendix.

Stylolites

Stylolites crosscut the color banding, the lattice-preferred orientation foliation and grain-shape fabric of the Fletcher marble and ductile fold structures. The stylolites occur in both dolomitic and calcitic marble and represents pressure solution under low-grade conditions. The insoluble material is comprised of chlorite and graphite (Figure 6b).

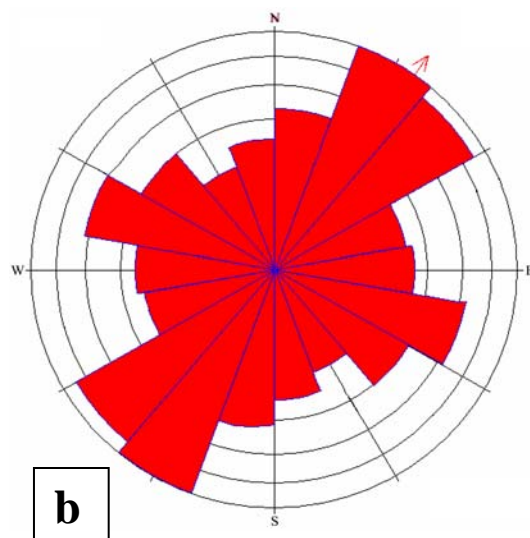
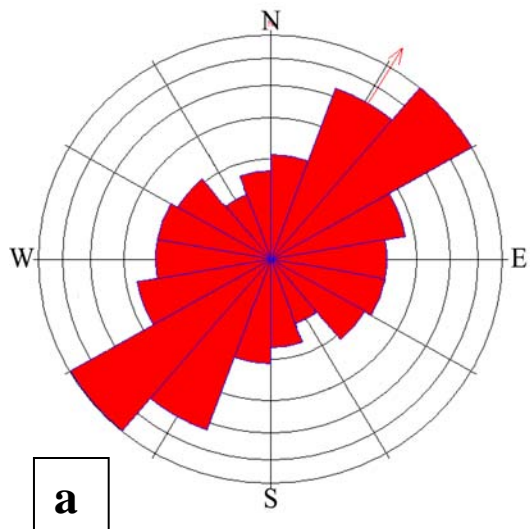


Figure 32. Jointing in the Brevard phyllonite and Fletcher marble. (a) Rose diagram showing trends in strike of jointing within the Brevard phyllonite, N=100. Photograph of jointing in an outcrop of the Brevard phyllonite. Photograph on the right shows jointing in outcrop. (b) Rose diagram showing multiple strike trends of jointing within the Fletcher marble, N=257. Photograph on the right shows jointing in outcrop.

Lineations

Linear elements observed during the field mapping include slickenlines and fold axes. These features occur within both lithodemes, however, the slickenlines are easier to recognize in the Fletcher marble than in the Brevard phyllonite.

Slickenlines generally occur along fault planes and along the layers of slip in folds within the Fletcher marble and are composed of linear fine-grained aggregates of calcite and quartz. Some of the slickenlines measured are related to the northwest-directed reverse dip-slip faulting (Figure 33). These slickenlines are hard to discern along the exposed footwall of the northern boundary fault because they are subject to weathering and abrasion due to quarrying activity. Most of the slickenlines that represent tops to the northwest reverse faulting were measured from fresh exposures on the hanging wall side of the quarry. A second population of slickenlines trend and plunges generally to the south. These slickenlines form perpendicular to the hinge lines folds in the marble.

A small number of fold axes were measured from folds in both lithodemes during the study (Figure 34). The folds axes generally trend and plunge to the south and southeast, while a smaller number trend and plunge to the northeast. Specific orientation and description of fold axes is described in the following section.

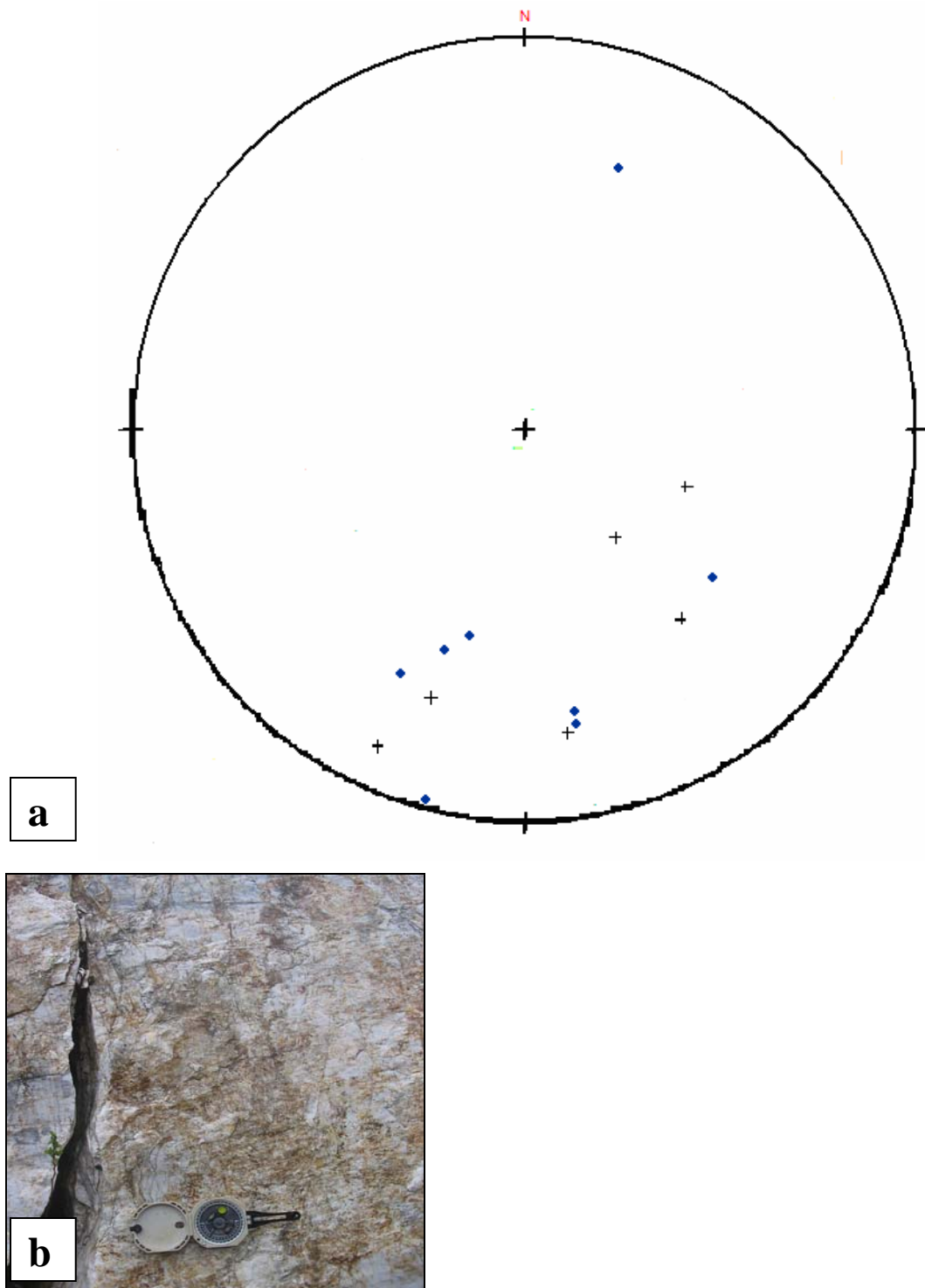
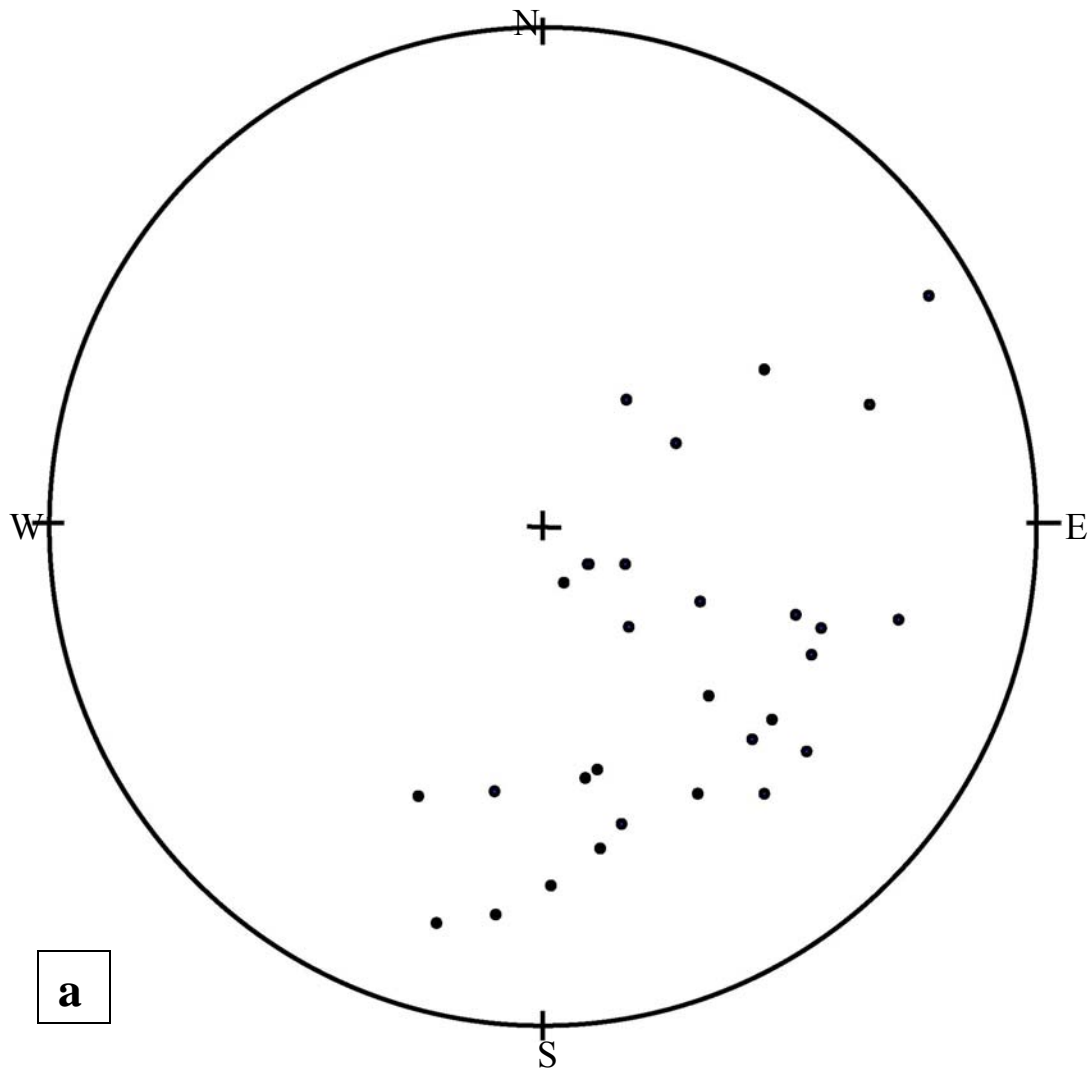


Figure 33. Slickenlines orientations within the Fletcher marble. (a) Equal area, lower hemisphere stereogram, N=13. Closed circles are slickenlines with dip-slip sense to SW. Crosses are slickenlines with dip-slip sense to the NW. (b) Photograph of slickenlines in outcrop.



a



b

Figure 34. Fold axes within study area. (a) Equal-area, lower hemisphere stereogram, N=27. Most fold axes trend and plunge to the southeast. (b) Photograph of fold axes in outcrop of phyllonite.

Fold Structures in the Brevard phyllonite

Intrafolial folds

Intrafolial folds deform porphyroclasts containing sillimanite-biotite grade minerals, and quartz ribbons within the Brevard phyllonite (Figures 17a and c). The folds are recumbent, tight to isoclinal and lie axial planar to schistosity. Shear bands crosscut the intrafolial folds along their axial planes and detached the fold limbs and translated them parallel to the axial planar foliation.

Mesoscopic folds

Mesoscopic folding occurs in the Brevard phyllonite and is well-developed adjacent footwall of the fault-line scarp. The most prominent folds occur along strike adjacent to the northern fault-line scarp, next to the quarry pit access ramp (Figure 35). These folds are asymmetric, gentle to open, and contain axial planes that are tilted to the southwest. The folds are generally 1 to 3 meters length, and their amplitude is approximately 0.3 meters. The fold axes generally trend south-southeast and plunges 23° to the south (Figure 35). Drag folds in the marble are tight, asymmetric, inclined to the southwest and measure 0.3 meters in length and 15.0 cm in amplitude.

Fold Structures in the Fletcher marble

Mesoscale folds are observed within in the Fletcher marble. The observed folds have a wavelength of 10 to 25 cm and have a low amplitude. Open and isoclinal fold axes trend from S 40° to 65° E and plunge 61° to 75° to the southeast (Figure 36). Some of the folding is crosscut by stylolite development. Folds that display layer parallel-slip also appear to have occurred along

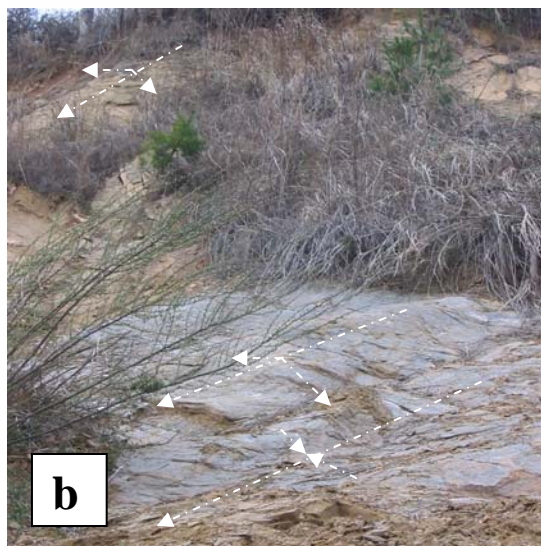
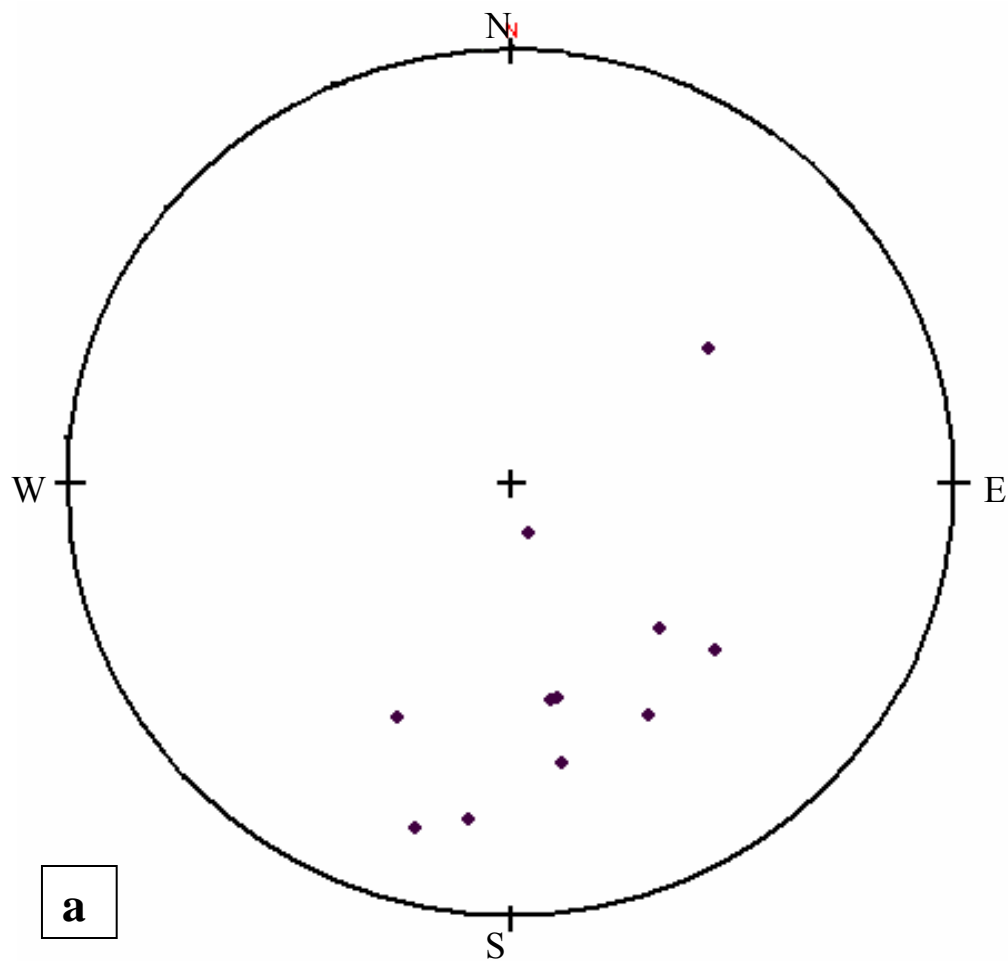


Figure 35. Mesoscopic fold axes within Brevard phyllonite. (a) Equal area, lower hemisphere stereogram N=11. (b) Photograph of folding in outcrop, arrows indicates the fold axes and limbs.

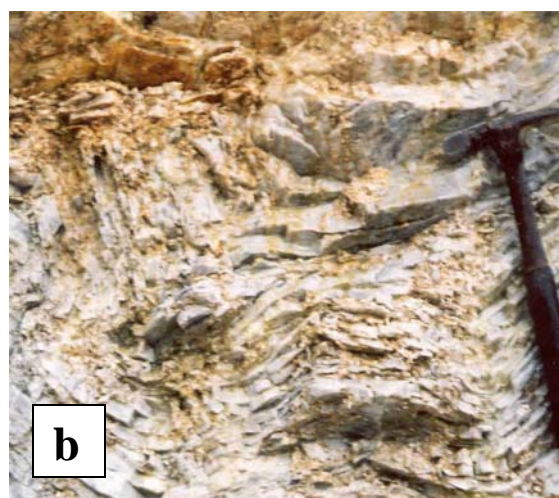
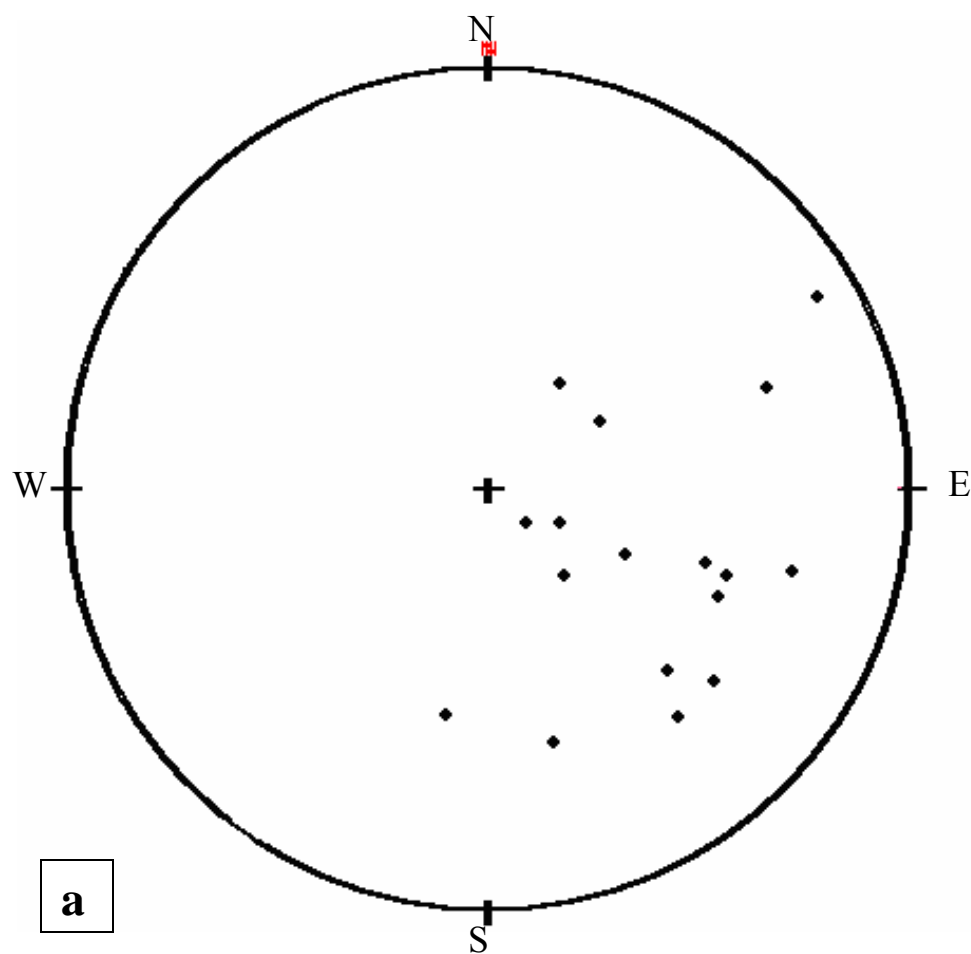


Figure 36. Folds within the Fletcher marble. (a) Equal area, lower hemisphere stereogram, N=17. Two populations of fold axes recognized; one oriented to the southeast, the other oriented to the northeast. (b) and (c) Photographs of folding in outcrop.

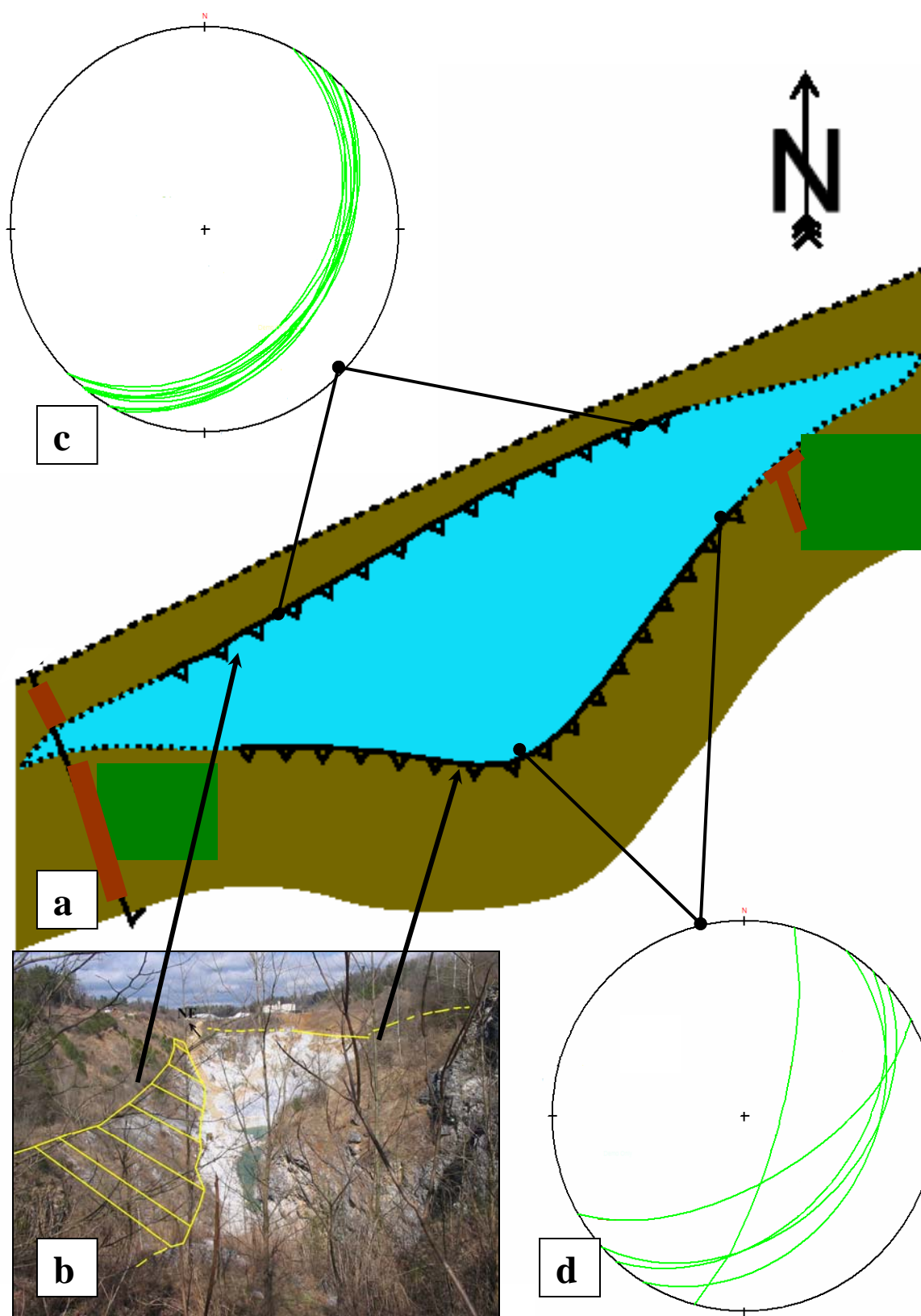
the pre-existing color banding present within the marble (Figure 36). Thickness of the layers usually ranges from 0.25 cm to 1.0 m thick, however, some folds have been observed with layering as thick as 5 to 8 meters. A minor amount of white mica or talc is observed between the slip-surfaces, in addition to slickenlines. The slickenlines are dolomitic to calcitic, contain some quartz and lie perpendicular the hinge line of the fold.

Brittle faults

Brittle faults are observed throughout the study area. The contact between the Brevard phyllonite and Fletcher marble is sharp, contains fault gouge, and slickenlines indicative of brittle faulting. In addition, mesoscale brittle faults displaying offset and slickenlines are observed within the Fletcher marble.

The northwestern wall of the Fletcher Limestone Company quarry constitutes a fault boundary between the Fletcher marble and the Brevard phyllonite (Plate A, Figure 37). This fault line scarp follows a general trend of N 38° E and dips 35° to the southeast (Figure 37). Though it is well exposed, erosion and weathering have deteriorated the surface features on the scarp (Plate A, Figure 37). A few calcite slickenlines were observed plunging S 40° E at an angle of 60° SE and demonstrate a top to the northwest sense of motion. Tabular-shaped bodies of fault gouge are observed along the surface of the fault-line scarp. The fault gouge measures 3.0 to 17.0 cm thick. Fresh exposures are composed of fine-grained quartz and calcite that displays fibrous to flaky habit, with occasional vugs. The vugs are filled with gray- white, fine to medium crystalline calcite, quartz druse 0.4 cm in length and cubic pyrite that is 1 to 3 mm in width. Liu (1991) inferred this contact to be part of Rosman Fault (Horton, 1982), based upon much of the same evidence.

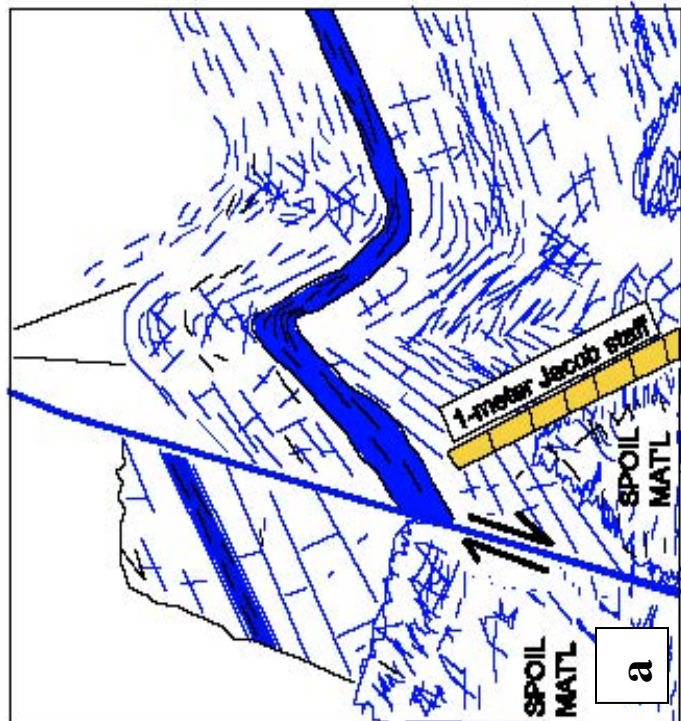
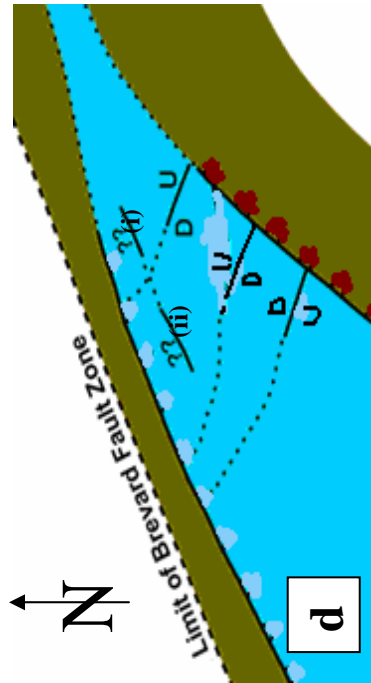
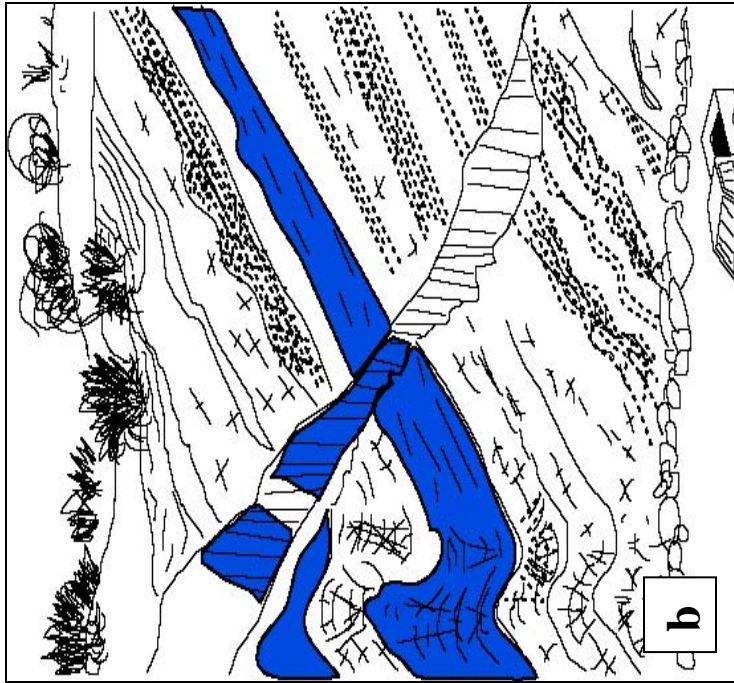
Figure 37. Orientation of boundary faults in study area. (a) Sketch map from Plate A shown with respect to the boundary faults, not to scale. (b) Photograph along strike, oriented to the northeast; yellow lines indicate position of fault-line scarps. (c) Equal area stereogram of the northern fault, lower hemisphere, N=16. (d) Equal area stereogram of the southern fault, lower hemisphere, N=5.



The southern fault-line scarp is partially obscured by overburden and is represented by a few outcroppings of freshly exposed fault gouge that appear to cap the marble. The orientation of the southern boundary fault, measured from the few exposures that were observed, is N 39° E, dipping 50° to the southeast (Figure 37). The thickness of exposed fault gouge was measured to be 20.0 to 74.0 cm thick.

Meter- to decimeter-scale faults in the Fletcher marble display meter-scale throws to the northwest and southwest (Figure 38). The most noticeable fault is present on the southern wall, facing the northeastern pit workings. The fault is curvilinear and strikes N 85° E and dips 70° to the southeast. The fault extends from pit floor to the top of the quarry, and appears to merge with additional fault splays (Figures 38b and c). Centimeter-scale slickenlines having a southeastern trend and plunge, dip-slip to the northwest were observed on this fault plane. A number of smaller-scale faults contain centimeter scale offsets and slickenlines that indicate reverse faulting with dip-slip to the west (Figure 38d).

Figure 38. Sketch drawings of outcrop scale faulting within the Fletcher marble. Drawings and photographs show relative fault throws observed within the marble deposit. (a) Hand drawn picture of flexural slip fold antiform within marble, which is crosscut by high-angle reverse fault, headwall up-thrown to the southwest (to the right). Point of view is to the southeast. (b) Hand drawn picture of the quarry wall, viewing to the southeast. Truck is in foreground for scale. Folded marble is crosscut by a curvilinear fault, which shows the southwestern side (headwall) being pushed to the northwest toward the truck. The northeastern wall (footwall) is pushed to the southeast away from the truck. (c) Photograph of the same wall, showing faulting. (d) Diagram showing the relative position and throw of faults within the quarry. Fault 'a' corresponds to (i), fault 'b' corresponds to (ii). Dotted lines mark approximated location of concealed faults. 'U' is headwall side, relative movement up. 'D' is footwall side, relative movement down.



COMPARATIVE PETROGRAPHY OF SIMILAR CARBONATES

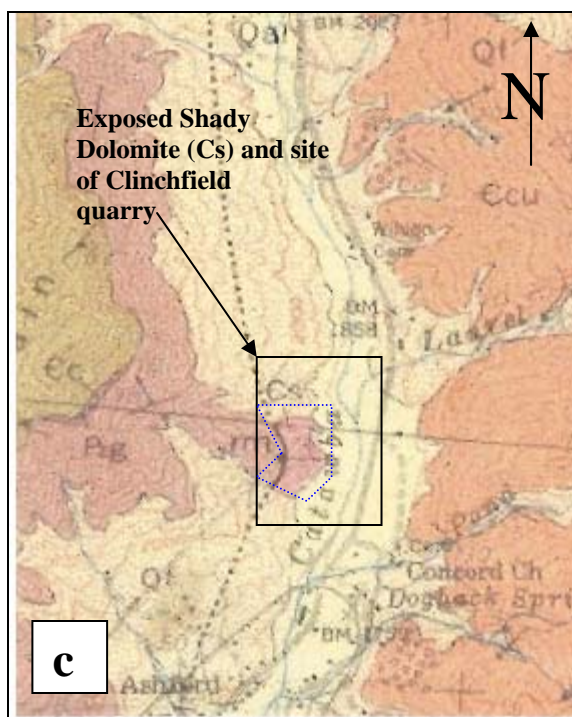
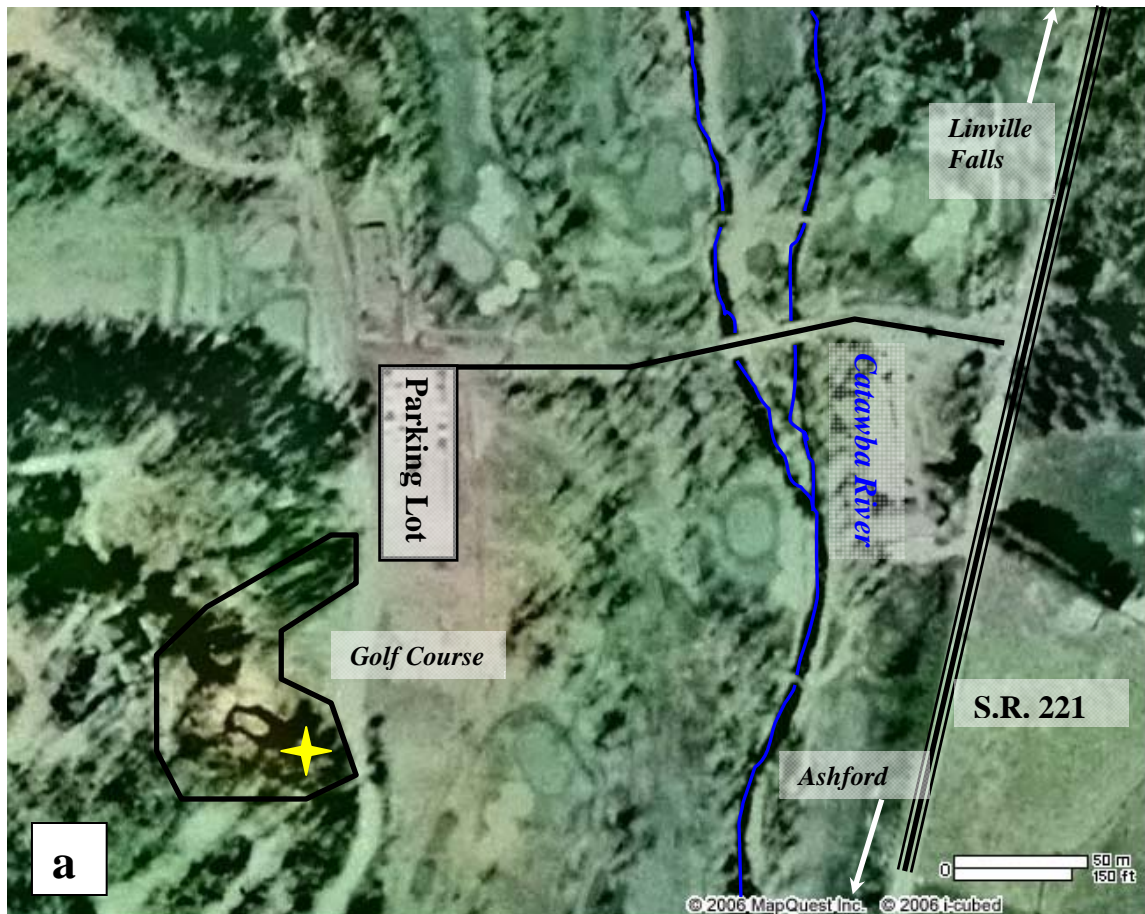
Additional samples were collected from the Linville Falls area, and the Bandana marble quarry near Bandana, N.C. to permit a comparison of the carbonates with this study.

Linville Falls

Keith (1905) was the first to map the carbonates in the area. He had correlated them to the Cambrian Shady Dolomite formation in Tennessee based upon similar lithologic features. The carbonates are considered to be a dismembered formation (Reed, 1964, Bryant, 1965) and are correlated to the Shady Dolomite (Bryant and Reed, 1960). They are considered correlative to the Shady Dolomite in Tennessee, based upon lithologic similarity and stratigraphic position with an overlying *Scolithus*-bearing quartzite that is considered similar to the Erwin Formation of the Chilhowee Group (Reed, 1964, p. 18). Reed (1964) and Bryant (1965) consider the dismembered Shady Dolomite in the Linville Falls quadrangle to be representative material from footwall of the Paleozoic platform.

A sample of the Shady Dolomite was collected from the abandoned Clinchfield Lime Company quarry (Conrad, 1960), which lies 2460 meters north of Ashford, N.C. and 200 meters west of the North Fork Catawba River (Figure 39a and b). Reed (1964, p. 17) specifically mentions the quarry as a type sample of the Shady Dolomite within the Linville Falls Quadrangle (Figure 39c). The site has been developed into a golf course and is accessible with permission of the golf club owner. Conrad (1960) reported that limestone was mined from the quarry from 1916 to 1940. The quarry lies within the hillside and has a width of 61 meters with walls that extend 31 meters high (Conrad, 1960). The dolomite body dips westward into the hillside.

Figure 39. Location map of the Clinchfield Lime Company quarry. (a) The quarry (outlined) and sampling site (star) is indicated. The quarry is accessible from the parking lot via a service road to the south. (b) Strip map to the quarry site. (c) Geologic map (modified from Keith and Sterrett, 1954) showing thrust slice of Shady Dolomite.



Excavating the dolomite produced large amounts of overburden, which made continued economic development unprofitable (Conrad, 1960).

The Shady Dolomite is best exposed along a back wall of an abandoned limestone quarry. The rock has a tan color on weathered surfaces, dark gray on fresh exposures. The rock is very fine-grained but also contains coarser grained dolomitic veins that randomly crosscut the fine-grained rock fabric. Texturally it is massive, nearly featureless with the exception of a pervasive jointing that crosscuts the rock (Figure 40a). The joints are well-defined, that break the rock mass into rhombohedron-shaped blocks 0.3 m to 0.7 m wide. At least three orthogonal joint sets are present in outcrop, which create very dangerous and unstable slope and overhang conditions within the quarry (Figure 40b).

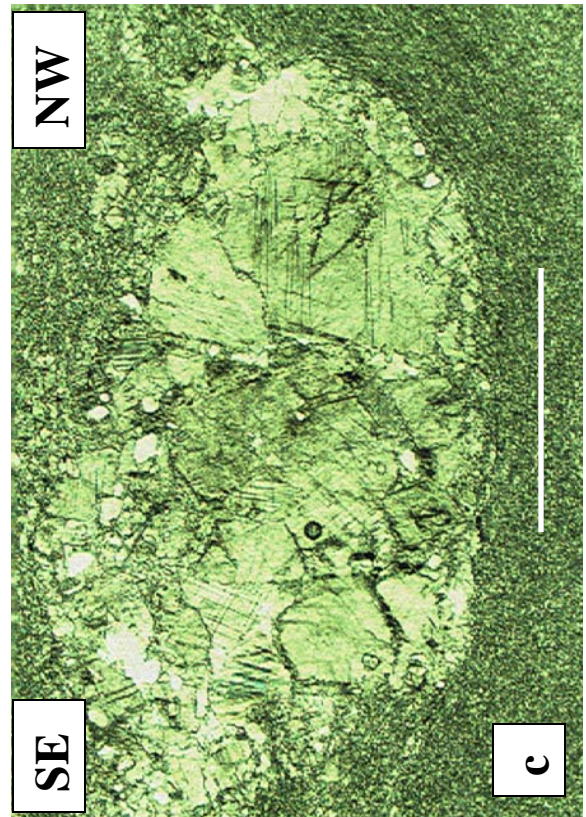
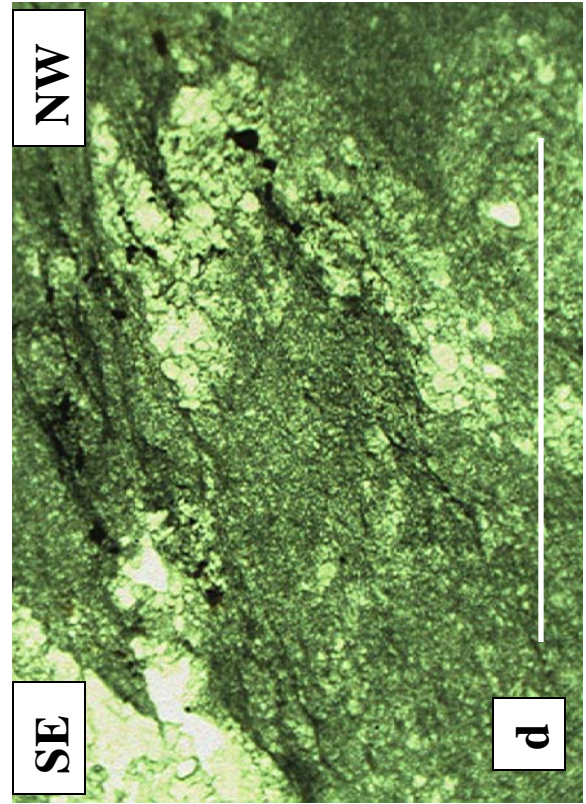
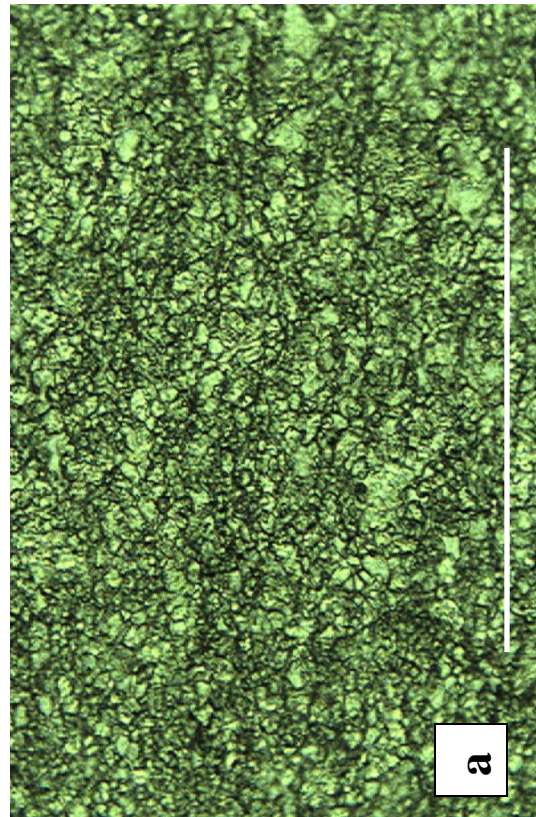
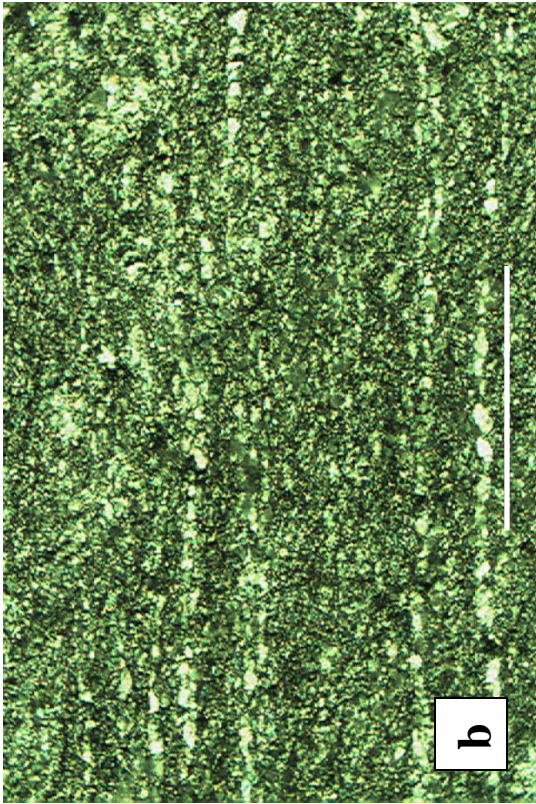
The rock is composed predominantly of dolomite, with lesser amounts of calcite, quartz and a trace of opaque minerals. No phyllosilicates are present. Texturally, it is a marble ultramylonite (SLTTM 1.0, 2004), containing 90 to 100% matrix. There is no relict sedimentary bedding or primary structures present.

The matrix consists of a very finely crystalline to aphanocrystalline (0.01 mm – 0.005 mm), equigranular-interlobate mosaic of dolomite grains (Figure 41a). The dolomite grains display a strongly developed shape preferred fabric. Shear ribbons composed of finely crystalline xenotopic dolomite occur with the very fine-grained matrix and display development parallel to foliation (Figure 41b). The ribbons are typically one grain thick (0.02 mm) and range from 0.5 to 2.0 mm in length. The fine-grained matrix surrounds and forms moderately well-defined embayments around rotated dolomitic porphyroclasts. The porphyroclasts are a minor component of the mylonite-series rock and comprise less than 10% of the rock.

Figure 40. Shady Dolomite outcropping in the abandoned Clinchfield quarry.
(a) Weathered and fresh exposures of the Shady dolomite. Note the massive, featureless texture of the rock. The most noticeable features are orthogonal joint sets. (b) Closer view of an overhanging outcrop within the quarry wall. Note how the jointing crosscuts the rock mass to produce hazardous overhanging conditions.



Figure 41. Fabrics elements within Shady Dolomite recovered from the abandoned Clinchfield quarry. (a) Photomicrograph of extremely-fine to aphanocrystalline matrix. Note that grain fabric is equigranular-interlobate. Much of the rock is comprised of this fabric. (b) Shear ribbons comprised of fine-grained xenotopic dolomite within a matrix of aphanocrystalline dolomite. Note the ribbons are only one grain thick. (c) Rare dolomitic porphyroclast within the mylonitic fabric. Note that ductile flowage around the porphyroclast and embayments seem to indicate NW dextral shear sense. (d) Possible flowage fold that is axial planar to the shape fabric. All photomicrographs were taken under plane polarized light; bar = 1.0 mm.



The porphyroclasts are oblong shaped, mantled δ -type porphyroclasts that measure 2.0 to 3.0 mm in length and 2.5 mm in width (Figure 41c). The cores are comprised of coarsely crystalline dolomite that displays type-IV twinning and subgrain development along grain boundaries. The coarse-grained dolomite ranges in size from 0.5 to 0.8 mm in size. Its grain boundary displays subgrain recrystallization, which forms finely-crystalline grains that encompass it. Coarsely-crystalline dolomite also occurs within sheared veins as occasional xenotopic vein fill.

Sheared veins displaying isoclinal folding lie axial planar to the shape preferred fabric foliation (Figure 41d). The veins contain medium- to finely-crystalline, xenotopic, inequigranular-interlobate, dolomite and calcite, with lesser amounts of coarsely-crystalline dolomite and quartz.

Bandana marble

The only significant outcroppings of marble within in the Ashe Metamorphic and Tallulah Falls Metamorphic Suite occur near Bandana, N.C., approximately 60 kilometers northwest of the study area.

The Bandana marble contains a mineral assemblage of dolomite + white mica + apatite + tremolite + quartz. Hand samples of the Bandana marble are white in color, medium- to extremely coarsely-crystalline, and have a granoblastic texture. It is composed of 98.8% dolomite (Millington and others, 2006) and has an average grain size of 2.0 to 3.0 mm that weathers into talus particles of similar size. In thin section, the Bandana marble is comprised of extremely coarse- to medium-crystalline, polygonal to xenotopic grains of dolomite (Figures 42a and b). These grains generally have straight-serrated grain boundaries and collectively form an

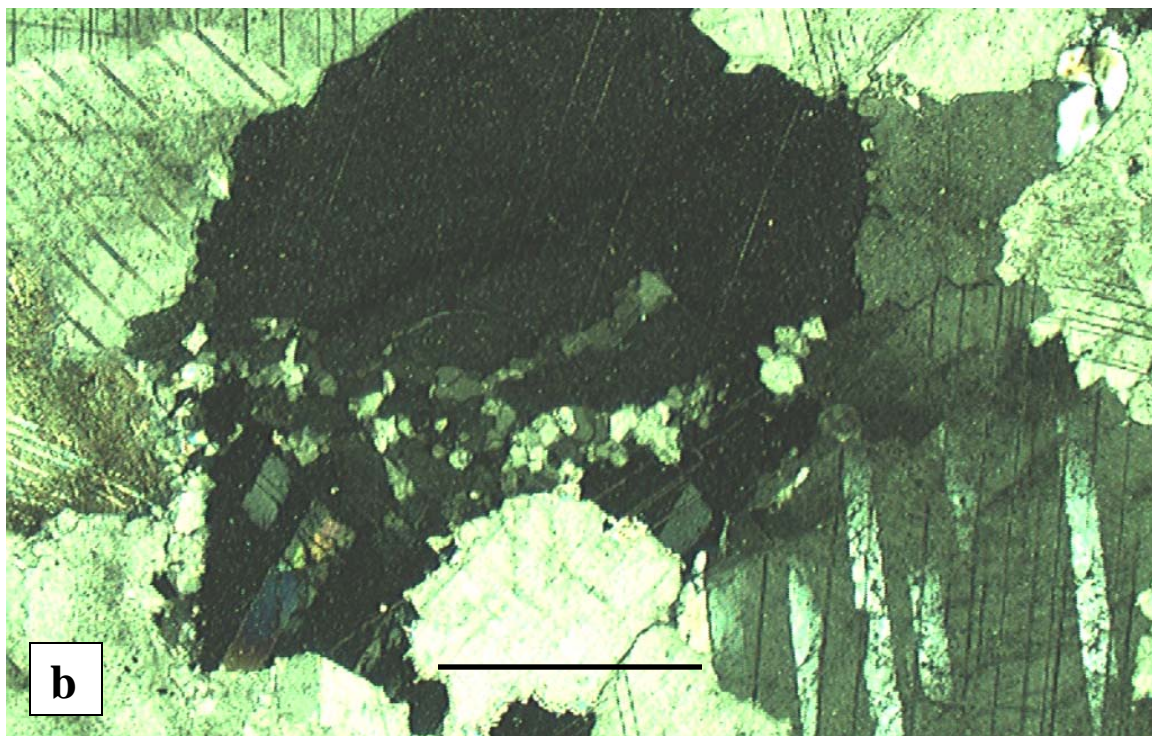
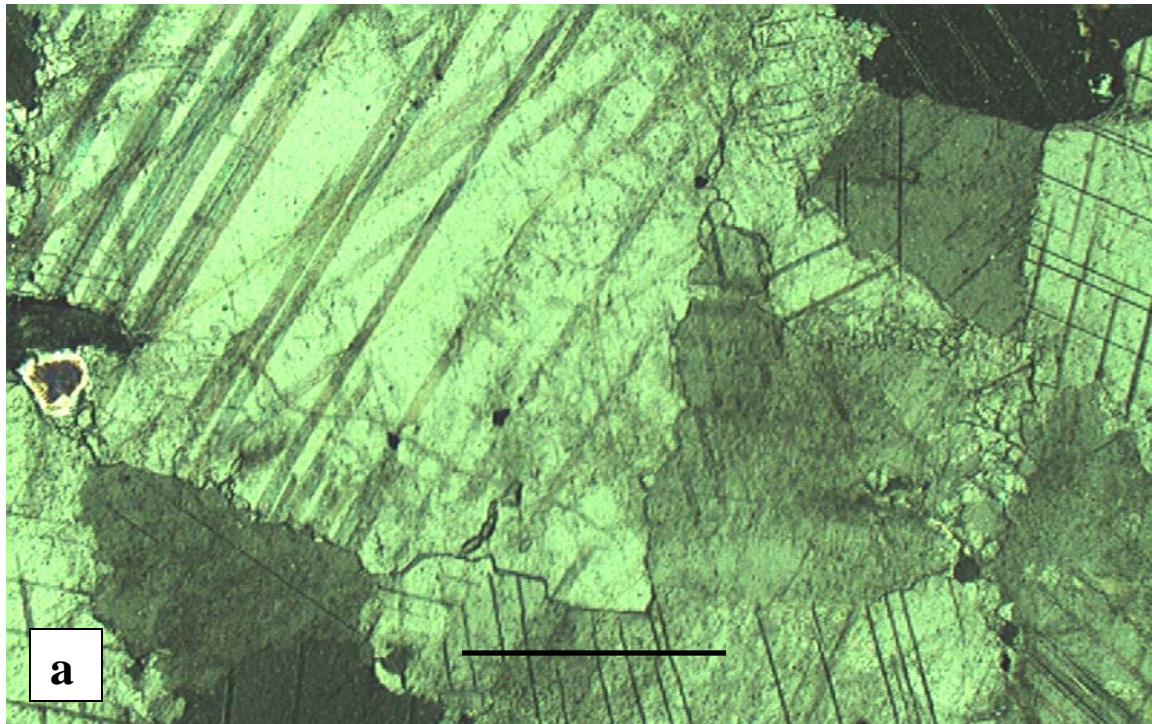


Figure 42. Photomicrographs of the Bandana marble. a) Extremely coarsely-crystalline xenotopic dolomite with interlobate to seriate grain boundaries. Microtexture records a period of extreme crystal growth ($T > 300^{\circ}\text{C}$) followed by strain. b) Subgrain development within extremely coarsely-crystalline dolomite from the Bandana marble.

equigranular-polygonal to inequigranular-polygonal shaped crystalline mosaic (Figure 42a). Subgrains of finely- crystalline dolomite were observed to mantle the grain boundaries of some coarse- and extremely coarse-grains (Figure 42b). The grains display well-defined twinning. Trace amounts of quartz, white mica, and apatite occur as finely-crystalline, xenotopic inclusions within dolomite. Tremolite occurs as intercrystalline, finely-crystalline, acicular grains. White mica also occurs as medium- to finely-crystalline lepidoblastic grains between grains of dolomite. The Bandana marble may contain a lattice-preferred orientation based upon a visual test using the gypsum plate of a petrographic light microscope. Based upon the dominant texture in the rock it is classified as a marble ‘granofels’ in the sense of the SLTTM 1.0 (2004).

The Bandana marble is surrounded by an exoskarn that contains an assortment of minerals including tremolite and diopside. Millington and others (2006) derived a peak metamorphic temperature of 600°C to 650°C from samples taken from the exoskarn adjacent to the marble deposit.

METAMORPHIC HISTORY

The rocks of the study area record a history of retrograde metamorphism. Peak metamorphic conditions, prior to the retrograde metamorphism, were well into upper amphibolite facies. These high-grade mineral assemblages predate the earliest recognized deformation found in this study. Retrograde metamorphism correlates to the crosscutting features observed in the study area. The following discussion will identify a number of pressure and temperature systems used to evaluate metamorphic conditions for rocks of the study area. Conditions of metamorphism are determined from the mineral assemblages observed. The metamorphic conditions and deformation sequence is then correlated to the regional geologic setting.

Pressure– temperature systems used for interpretation

The Brevard phyllonite contains porphyroclasts with amphibolite facies mineral assemblages that record the highest grade of metamorphism. These mineral assemblages suggest that the protolith was of pelitic composition. Pressure and temperature constraints for these mineral assemblages were determined by using several equilibrium systems. These systems are the K-Na-Fe-Al-Si-H (KNFASH) system (Figure 43; Powell and Holland, 1990, in Bucher and Frey, 1994, p. 203, their figure 7.4) and the Fe-Al-Si-O-H (FASH) system (Figure 44; Bucher and Frey, 1994, p.199, their figure 7.3). Amphibolite facies mineral assemblages in the Fletcher marble were analyzed using phase diagrams for dolomitic marbles containing excess carbonate (Figure 45; Bucher and Frey, 1994, p. 175, their figure 6.2). Syntectonic veining and mineralization required the use of a second phase relationship that considers quartz and calcite in excess (Figure 46; Bucher and Frey, 1994, p. 177, their figure 6.3). Published parameters for

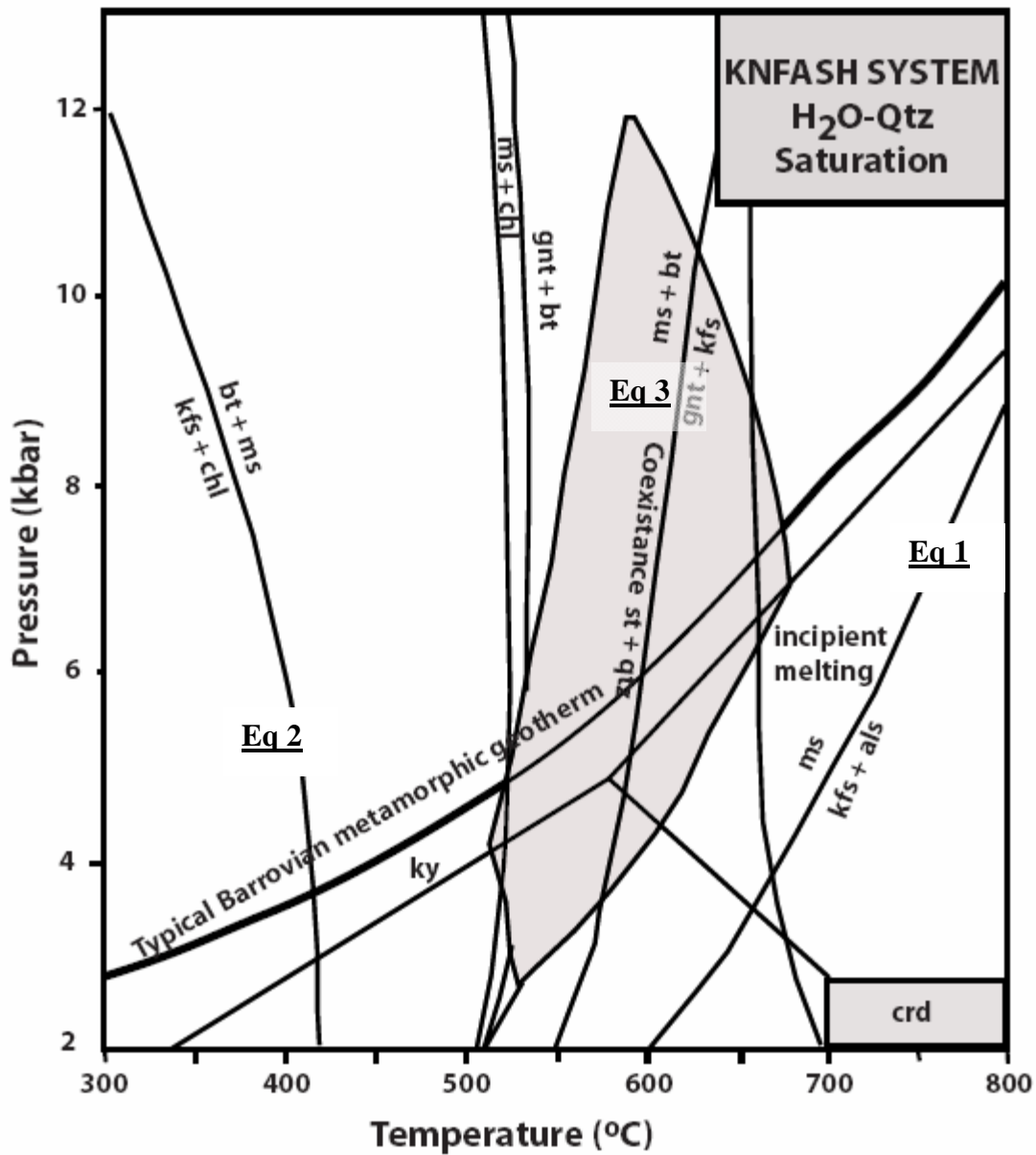


Figure 43. Phase diagram for mica reactions in metapelites. Redrawn from Bucher and Frey (1994, figure 7.4). Central shaded area represents quartz and staurolite stability field. Corner shaded area represents cordierite and hercynite reactions.

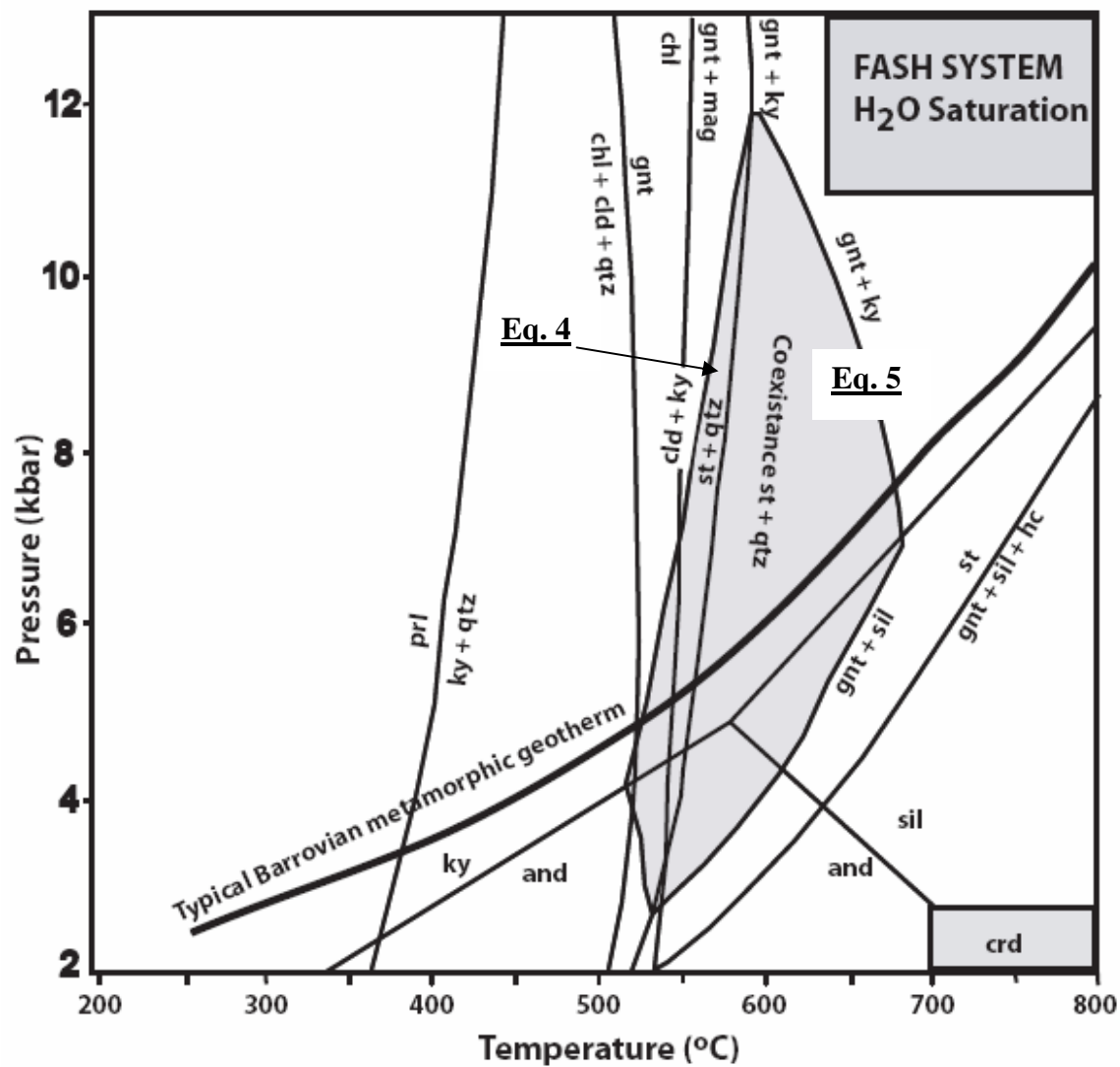


Figure 44. Phase diagram for reactions involving staurolite and quartz in metapelites. Central shaded area represents the coexistence of quartz and staurolite. Redrawn from Bucher and Frey (1994, figure 7.3). Corner shaded area represents cordierite and hercynite reactions (not observed).

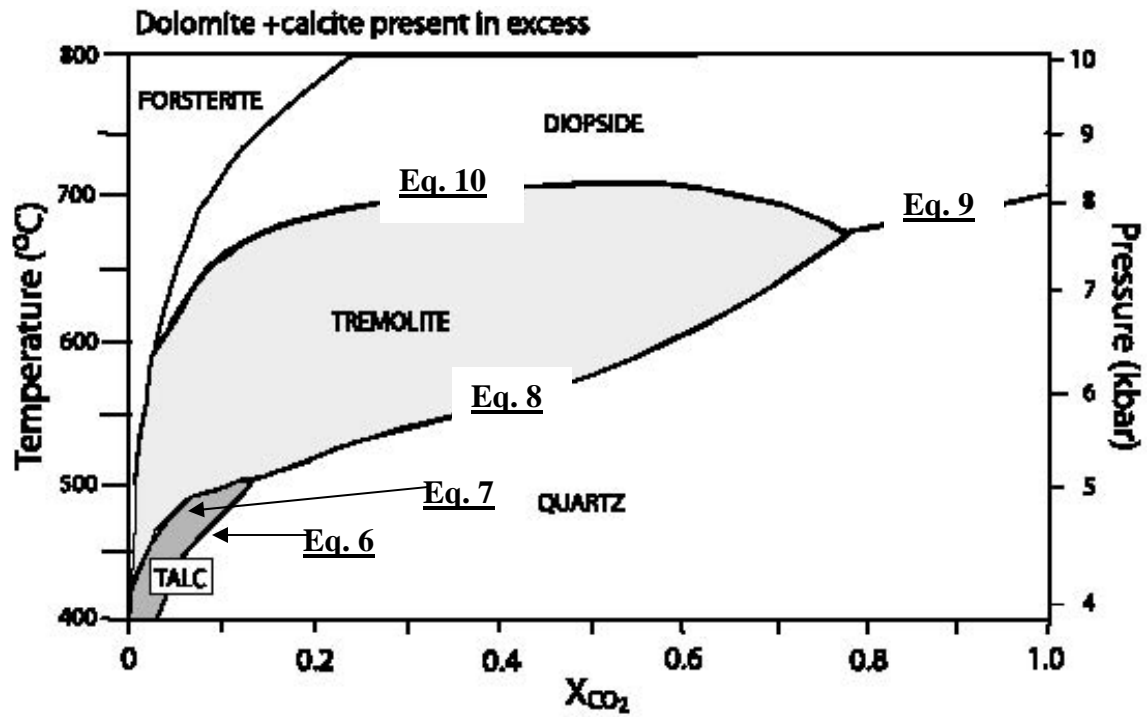


Figure 45. Phase relationship in dolomitic marble containing excess dolomite and calcite, redrawn from Bucher and Frey (1994, figure 6.2).

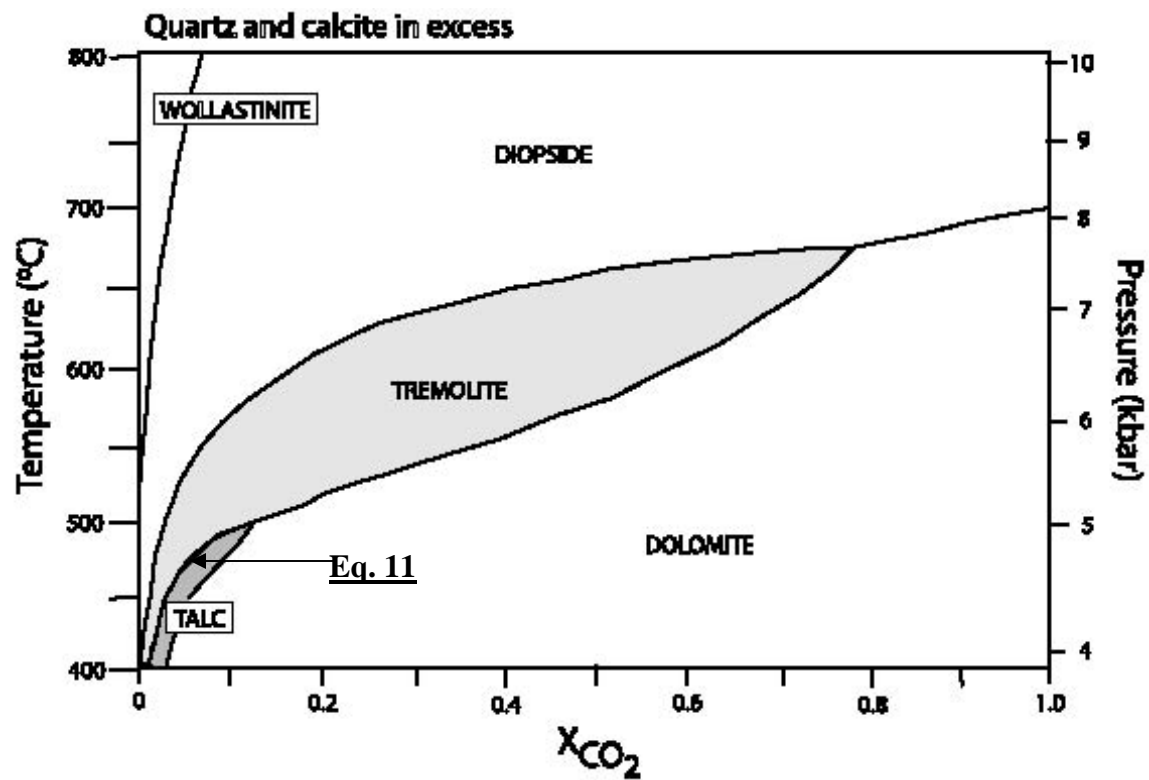


Figure 46. Phase relationship in marble containing excess calcite and quartz, redrawn from Bucher and Frey (1994, figure 6.3).

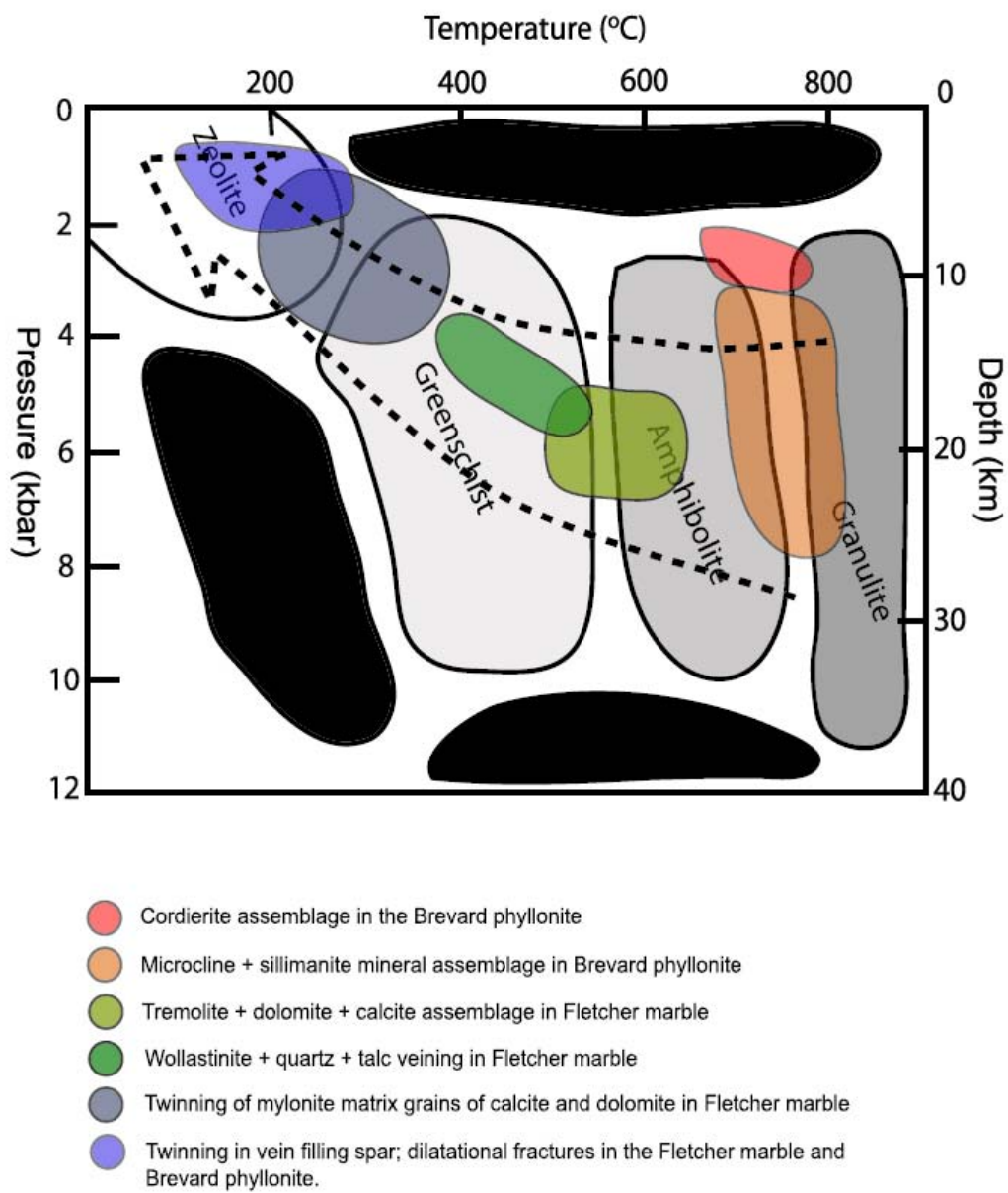


Figure 47. Pressure and temperature diagram showing path of retrograde metamorphism that is recorded within the mineral assemblages of the rocks from the study area.

twin morphologies in calcite (Burkhard, 1993) and dolomite (Shelley, 1993 p. 353) facilitate the evaluation of low-grade metamorphic conditions within the Fletcher marble. Constraints of metamorphism, derived from the observed mineral assemblages, are plotted on a pressure and temperature diagram, from which, a pathway of retrograde metamorphic can be inferred (Figure 47).

Geothermometry and Geobarometry

Upper amphibolite facies mineral assemblages in the Brevard phyllonite

The Brevard phyllonite contains sparsely disseminated mineral porphyroclasts within its matrix that are indicative of upper amphibolite facies conditions. These include microcline porphyroclasts containing sillimanite inclusions and porphyroclasts of cordierite that contain inclusions quartz and white mica. Referring to the K-Na-Fe-Al-Si-H (KNFASH) system (Figure 43), the following mineral reaction defines the lower stability limit for the formation of microcline in the presence of sillimanite:

Eq. 1) muscovite + quartz = K-feldspar + sillimanite + H₂O at 675°C, 300 Mpa.

The upper and lower temperature and pressure constraints for K-feldspar and sillimanite are $675^{\circ}\text{C} \leq T \leq 800^{\circ}\text{C}$, $300 \text{ Mpa} \leq P \leq 800 \text{ Mpa}$ (Figure 43).

Cordierite crystallizes in the presence of muscovite within the temperature and pressure regime $700^{\circ}\text{C} \leq T \leq 800^{\circ}\text{C}$ and $200 \text{ Mpa} \leq P \leq 300 \text{ Mpa}$ (Figure 43). Given a bulk composition that contains a higher Mg-content, the temperature at which cordierite is expected to form should decrease to 625-680°C. This condition may be applicable if the protolith contained dolomitic

mudrocks. Therefore, a wider temperature and pressure regime that encompasses the occurrence of cordierite may lie within $625^{\circ}\text{C} \leq T \leq 800^{\circ}\text{C}$ and $200 \text{ Mpa} \leq P \leq 300 \text{ Mpa}$ (Figure 43).

Exotic rock metamorphic mineral assemblages

The Fe-Al-Si-H (FASH) system (Figure 44) describes the stability conditions for staurolite \pm kyanite + white mica mineral assemblages that are present in fault entrained (“exotic”) slices of staurolite schist within the Brevard phyllonite. The following mineral reaction defines the lower stability limit of staurolite:

Eq. 4) $8 \text{ chloritoid} + 10 \text{ kyanite} = 2 \text{ staurolite} + 3 \text{ quartz} + 4\text{H}_2\text{O}$ at 510°C , 400 Mpa.

Staurolite, kyanite and quartz remain stable through a temperature and pressure regime of $510^{\circ}\text{C} \leq T \leq 670^{\circ}\text{C}$ and $250 \text{ Mpa} \leq P \leq 1200 \text{ Mpa}$. Above 670°C , staurolite begins to decompose to kyanite and garnet by the reaction:

Eq. 5) $75 \text{ staurolite} + 312 \text{ quartz} = 100 \text{ garnet} + 575 \text{ kyanite} + 150 \text{ H}_2\text{O}$.

The pressure and temperature regime for the assemblage kyanite + garnet + white mica is considered using the FASH system for idocrase-bearing schistose exotic rocks. The lower limit of kyanite formation is the same as equation 5. This reaction consumes staurolite to produce kyanite and garnet in the presence of quartz. Partial melting marks the upper stability limit for the mineral assemblage. Therefore, the effective temperature and pressure realm that would support this mineral assemblage is $670^{\circ}\text{C} \leq T \leq 800^{\circ}\text{C}$ and $650 \text{ Mpa} \leq P \leq 1300 \text{ Mpa}$ (Figure

44). The pressure and temperature realms of these two exotic rocks indicate that they sustained peak metamorphic conditions that predate those attributed to the D₁ of this study.

Lower amphibolite facies assemblages within the Brevard phyllonite

Porphyroclasts containing biotite, white mica, and plagioclase record lower amphibolite facies metamorphism. Referring to the K-Na-Fe-Al-Si-H (KNFASH) system (Figure 43) the lower stability limit of biotite is:

Eq. 2) 3 chlorite + 8 K-feldspar = 5 biotite + 3 muscovite + 9 quartz + 4H₂O at 420°C, 200 Mpa.

The upper stability limit of biotite in the presence of muscovite is:

Eq. 3) 1 muscovite + 1 biotite + 3 quartz = 1 garnet + 2 K-feldspar + 2 H₂O at 600°C, 400 Mpa.

The regime in which biotite crystallizes and remains in stable phase with muscovite is constrained to a temperature and pressure that ranges from $400^{\circ}\text{C} \leq T \leq 600^{\circ}\text{C}$ and $200 \text{ Mpa} \leq P \leq 400 \text{ Mpa}$ (Figure 43).

Lower amphibolite facies mineral assemblages in the Fletcher marble

The Fletcher marble contains a lower amphibolite facies mineral assemblage of tremolite + dolomite + calcite + (trace) quartz. Observed tremolite appears to be constrained to the protomylonitic domains within the marble and is exceedingly scarce within mylonitized

domains. Tremolite forms during the prograde reaction (Figure 45) of dolomite with quartz to form talc:

Eq. 6) $3 \text{ dolomite} + 4 \text{ quartz} + \text{H}_2\text{O} = \text{talc} + 3 \text{ calcite} + 3 \text{ CO}_2$ from 400 to 500°C and 400-500 Mpa.

Talc is consumed simultaneously by a second reaction (Figure 45) with calcite:

Eq. 7) $2 \text{ talc} + 3 \text{ calcite} = 1 \text{ tremolite} + \text{dolomite} + \text{CO}_2 + \text{H}_2\text{O}$ from 400 to 500°C and 400-500 Mpa.

These reactions go to completion at 500°C at 500 Mpa, where all available talc is consumed to form tremolite (Figure 45). This also coincides with the beginning of amphibolite facies conditions.

Continued prograde reactions will occur with water, quartz and dolomite to form additional tremolite:

Eq. 8) $5 \text{ dolomite} + 8 \text{ quartz} + \text{H}_2\text{O} = 1 \text{ tremolite} + 3 \text{ calcite} + 7 \text{ CO}_2$ from 500 to 660°C and 500 Mpa to 780 Mpa.

The maximum limit of metamorphic reactions would correspond to the production of diopside, which can occur by two different reaction pathways, the first being;

Eq. 9) $1 \text{ dolomite} + 2 \text{ quartz} = \text{diopside} + 2 \text{ CO}_2$ at 670°C and 780 Mpa, or

Eq. 10) $3 \text{ calcite} + 1 \text{ tremolite} = 1 \text{ dolomite} + 4 \text{ diopside} + 1 \text{ H}_2\text{O} + 1 \text{ CO}_2$ at 610°C and 680 Mpa .

The first reaction will produce diopside if there is an increase in temperature and enough quartz is present within the system to allow the prograde reaction to continue. If there were not enough quartz to drive the first reaction, the second reaction would be the only plausible way to generate diopside if there is enough tremolite present.

Small amounts of quartz are present within porphyroclasts and protomylonite domains. These domains only contain a fractional amount of tremolite, indicating that two significant factors might have affected tremolite crystallization within the protolith. The first limiting factor is the availability of quartz. Insufficient amounts of quartz will prevent talc forming and prevent tremolite forming. The second limiting factor is the availability of water to react with dolomite and quartz to produce talc. The trace amount of tremolite observed, and the presence of small amounts of intercrystalline quartz within the vicinity, suggests that early metamorphic conditions in the Fletcher marble were deficient in intercrystalline water. This suggests that either the protolith lost its intercrystalline water or it had become impermeable to fluid interaction prior to metamorphism. The lack of diopside in thin section indicates that the marble had not achieved the temperature required to drive the dolomite and quartz reaction to produce diopside. Based upon the mineral assemblages observed in protomylonitic domains, the Fletcher marble sustained temperature and pressure conditions of $500^\circ\text{C} \leq T < 610^\circ\text{C}$ and $500 \text{ Mpa} \leq P < 660 \text{ Mpa}$ (Figure 45).

Greenschist facies assemblages in the Fletcher marble

Loughlin and others (1921), in their study of the Fletcher marble, mentioned the presence of wollastonite associated with talc in quartz-filled veins, in addition to the possible presence of tremolite, for which they did not specify a location.

In this study, the calcitic marble contains more quartz than the dolomitic marble (Table 1). Thus, a pressure-temperature-composition diagram reflecting this is used to evaluate P-T conditions (Figure 46).

Bucher and Frey (1994, p. 177) indicate that wollastonite does not form in regional metamorphic rocks under closed system behaviour. More commonly, wollastonite forms in marble by the interaction with H₂O-enriched fluids along fractures or shear zones (Bucher and Frey, 1994, p.177). Temperature and pressure conditions of this event can be constrained using phase relationships of calcite and quartz-rich marbles and the talc producing reaction:

Eq. 11) $3 \text{ dolomite} + 4 \text{ quartz} + 1 \text{ H}_2\text{O} = 1 \text{ talc} + 3 \text{ calcite} + 3 \text{ CO}_2$ at 400°C and 400 Mpa.

This reaction may have taken place during quartz veining and wollastonite mineralization as reported by Loughlin and others (1921). The upper limit of the reaction would be the production of tremolite by the consumption of talc:

Eq. 11) $5 \text{ talc} + 6 \text{ calcite} + 4 \text{ quartz} = 3 \text{ tremolite} + 6 \text{ CO}_2 + 2 \text{ H}_2\text{O}$.

Loughlin and others (1921) do not specify where they observed tremolite and it has not been detected veins or in outcrop during this study. Based upon the phase relationship between talc

and tremolite (Figure 46), it appears that vein-fill mineralization occurred in a temperature realm of 450 to 500°C and at pressures of less than 500 Mpa. These conditions correspond to upper greenschist facies conditions that are associated with mylonitization of the Fletcher marble.

Dolomite and calcite twin geothermometry

Dolomite is considered to be precise geothermometer because it starts to twin at a minimum temperature of 300°C (Shelley, 1993, p.126), and develops well-defined twins when the temperature reaches 400°C (Shelley, 1993, p.81). Alternatively, given decreasing P-T conditions, high-grade deformation mechanisms would give way to twinning at 400°C.

Within the Fletcher marble, dolomite displaying type-IV twin morphologies occurs throughout the mylonitic fabric. This matrix also contains a greenschist facies mineral assemblage of white mica, talc, and chlorite. Because dolomite starts twinning at higher temperatures than calcite, the peak temperature during mylonitization was between 300 to 400°C. Calcite marble from the Fletcher quarry displays type IV twin morphology (Figures 8c and 11a) described by Burkhard (1993). Based upon his twin morphology classification, the minimum temperature for mylonitization was greater than 250°C. Therefore, the temperature range for lower greenschist facies metamorphism is between $250^{\circ}\text{C} < T \leq 400^{\circ}\text{C}$, which correlates with mylonitization.

Vein-filling mineralization in the Fletcher marble

Lower greenschist facies mineralization occurs primarily along joints and brittle fractures. Fibrous calcite and quartz vein-fill forms the first generation of mineralization to permeate the Fletcher marble post-dating the mylonitization. Quartz forms after syntaxial calcite,

occupying the central portion of the vein. The second vein mineralization contains blocky twinned calcite and dolomite. The maximum temperature of this event is estimated to be $150^{\circ}\text{C} < T < 300^{\circ}\text{C}$, using calcite twin morphology (Burkhard, 1993). However, twinning in calcite can occur at lower temperatures due applied stress.

Regional Correlations

The rocks exposed within the study area likely formed after the ~1100 Ma Grenville orogeny. Exposures of Grenville-age rocks occur 50 kilometers southwest of the study area within the Toxaway antiform. Based upon pelitic and carbonate composition, the Tallulah Falls Metamorphic Suite, Brevard phyllonite and Fletcher marble may be metasedimentary origin. Given their origin, there is no recognizable sedimentary bedding within these rocks. Diagenetic features recognized are probably secondary or relate to burial in a deep sedimentary basin. The first event recognized in the rocks of the study area is the M_1 high-grade metamorphism. Porphyroclasts in the Brevard phyllonite contain sillimanite, microcline and cordierite, which are associated with upper amphibolite facies metamorphism. The M_1 metamorphism predates the earliest recognized deformation fabric and contains very little if any textural evidence due to subsequent overprinting deformations. However, rocks that contain this M_1 and its associated fabric occur northwest of the study area. Dabagh (1975, 1981) reports that similar sillimanite-bearing rocks outcrop 19 kilometers northwest of the study area within the Eastern Blue Ridge (Figure 3). Two dextral strike-slip faults, the Brevard fault zone, and the newly discovered Cradle-of-Forestry-in-America-fault (Dockal, 2007) lie between these rocks and those of the study area. The implication of this is that the two faults may have played a role in distributing

high-grade lithologies within the Brevard phyllonite. The M_1 mineral assemblages are correlative to the M_1 of Dabbagh (1975), Dockal (2007), and the M_1 and M_2 of Mersch and others (2005)

Fault derived “exotic” rocks contain amphibolite facies assemblages that are related to localized contact metamorphism. The mineral assemblages are probably associated with the intrusion of pegmatitic dikes stemming from the Looking Glass pluton (Dockal 2001). Dabbagh (1975, 1981) reported that pegmatite dikes (350 to 320 Ma) intrude the Tallulah Falls Metamorphic Suite rocks near Fletcher. These *in situ* dikes may likely be coeval with the “exotic” pegmatite and idocrase bearing rocks within the Brevard phyllonite. Recent dating of the Spruce Pine (377.3 Ma; Trupe and others, 2003, 377.7 Ma; Johnson and others, 2001) and Looking Glass plutons (380 ± 3 Ma; Miller and others, 2000) constrains the timing of intrusion to coincide with Acadian deformation. Therefore, if the exotic rocks recording contact metamorphism are Acadian-Neocadian in age, the higher-grade M_1 porphyroclasts are at least Acadian, if not older.

The M_2 of this study correlates to lower amphibolite facies conditions that existed during the late Acadian deformation (Mersch and others, 2005). The Fletcher marble contains small amounts of tremolite, quartz and talc within protomylonite domains could have developed under these conditions. The M_2 metamorphism of this study correlates to the M_2 of Dabbagh (1975) and to the late M_2 of Mersch and others (2005).

The M_3 of this study is a retrograde greenschist facies event that corresponds to mylonitization. The Brevard phyllonite contains an M_3 mineral assemblage of white mica + chlorite \pm graphite. The marble contains M_3 mineral assemblage of white mica + chlorite + talc \pm graphite within the mylonitic fabric. In addition, the mylonite foliation appears to contain a syntectonic veining of wollastonite + talc + quartz + calcite \pm tremolite. Temperature conditions

inferred by twinning indicate that $250^{\circ}\text{C} < T \leq 400^{\circ}\text{C}$. The highest temperature for the greenschist facies mylonitization may have been $400^{\circ}\text{C} \leq T < 500^{\circ}\text{C}$ based upon the presence of talc within the mylonite foliation, and vein filling quartz, talc and possible tremolite. Lower temperatures are recorded by the presence of twinned dolomite and calcite, which is $250^{\circ}\text{C} < T \leq 400^{\circ}\text{C}$. The M_3 of this study is correlated to the M_2R of Dabbagh (1975) and the M_3 of Merschat and others (2005). The S_2 of this study correlates to the S_3 of Worley (2000), the white mica-preferred orientation foliation within the King Creek fault (Dockal, 2007), and the S_{4B} white mica preferred orientation foliation of Dockal (2007).

Transition from ductile to brittle deformation is represented by cataclastic fabric development, jointing, fracture propagation in both lithodemes. Last recognized motion associated with Late Alleghanian deformation resulted in the high-angle, dip-slip faulting to the northwest (Merschat and others, 2005). The M_4 of this study is correlative to the M_3 of Dabbagh (1975), and Merschat and others (2005).

PROTOLITH OF THE FLETCHER MARBLE

Previous workers (Reed and Bryant (1964), Hatcher (1971), Hatcher and others (1973), Liu (1991)) consider the Fletcher marble to be a low-grade metamorphic rock. Therefore, the protoliths proposed for the Fletcher marble are generally Lower Paleozoic carbonates that may be unmetamorphosed or sustained very low-grades of metamorphism (Reed and Bryant, 1964, Hatcher, 1971, Hatcher and others, 1973, Liu, 1991). The following discussion addresses what petrographic and analytical factors that may have influenced early workers (Reed and Bryant, 1964, Hatcher, 1971, Hatcher and others, 1973) to indicate a peak metamorphism for the Fletcher marble was no higher than greenschist facies. The discussion will

then focus on the proposed protoliths and how the information gained from this study qualifies or disqualifies them from future consideration.

Prior Assumptions Regarding the Fletcher marble

Reed and Bryant (1964) have characterized the Fletcher marble as a low-grade metasedimentary rock in outcrop. The basis of this assumption is a limited petrographic study of samples from the Fletcher marble (Reed and Bryant, 1964, Hatcher, 1971). Predominant mineral assemblages that workers observed in thin section and hand-sample were generally lower-greenschist facies (Reed and Bryant, 1964, Hatcher, 1971). In this study, petrographic analysis of the Fletcher marble indicates that tremolite has a domainal aspect and that it is most likely found within protomylonite domains. Therefore, it seems plausible that the petrographic analysis of Reed and Bryant (1964) and Hatcher (1971) may have overlooked the protomylonite domains, or they were absent from the limited amount of thin sections the workers studied.

The x-ray diffraction method (Graf and Goldsmith, 1958) used by Hatcher and others (1973) to establish paleotemperature is susceptible to yielding incorrect temperatures. Factors that lead to this include; insufficient amounts of dolomite in the presence of calcite, the uptake of Fe^{+2} or Mn^{+2} instead of Mg^{+2} in calcite, and Mg^{+2} loss in weathered samples (Graf and Goldsmith, 1958; Hatcher and others, 1973). The sampling procedures of Hatcher and others (1973) is not known, however, it appears that only one sample (sample #63 from Hatcher and others, 1973) was taken from the Fletcher Limestone Company quarry. Hatcher and others (1973) indicate that this sample does not contain dolomite. Given the first limitation to this method, a purely calcitic marble sample will yield low paleotemperature values. If samples are first screened for dolomite and calcite, then tested, it seems likely that higher paleotemperatures

would be recognized. Furthermore, selective sampling of the protomylonitic domains should reveal that middle-grade conditions reflecting lower amphibolite facies conditions are present. Therefore, the paleotemperature results of Hatcher and others (1973) are likely to represent only the Late-Alleghanian metamorphic conditions. They are not representative of the earlier higher-grade metamorphic history.

Shady Dolomite

Reed and Bryant (1964) suggested the Shady Dolomite, exposed near Linville Falls, N.C., as a protolith to the Fletcher marble. If the Shady Dolomite is the protolith of the Fletcher marble, the Shady Dolomite should contain protomylonite or earlier features. However, the Shady Dolomite is completely ultramylonitized under greenschist facies conditions and retains no earlier fabrics. The Fletcher marble retains protomylonite fabrics and higher-grade mineral assemblages that likely predate the fabrics and mineral assemblages observed within the Shady Dolomite. Therefore, given dissimilar microtextures, mineral assemblages, and deformational histories between the two carbonate bodies, it is unlikely that the Shady Dolomite is the protolith to the Fletcher marble.

Knox Dolomite

Several workers suggest that the Knox Dolomite is the protolith to the Fletcher marble and that is a slice from the Paleozoic subthrust, emplaced during the Late-Alleghanian faulting (Hatcher, 1971, 1978, 1989, 2001, Hatcher and others, 1973, Edelman and others, 1986, and Liu (1991). Supportive evidence includes; the underlying seismic geometry of the Brevard fault zone with respect to the Paleozoic subthrust (Edelman and others, 1986), presence of reverse dip-

slip slickenfibers along the fault line-scarp between the Fletcher marble and Brevard phyllonite (Lui, 1991), observed lower-grade mineralogy (Hatcher, 1971), and paleotemperatures no greater than 371°C (in Lui, 1991, p. 129) that is attributed to short-term frictional heating (Hatcher and others, 1973). If the Fletcher marble belonged to this carbonate bank, two arguments need to be addressed.

Discrepancies exist between early petrography (Reed and Bryant, 1964, Hatcher, 1971), paleotemperatures of Hatcher and others (1973) and the mineralogy observed in this study. The presence tremolite within the Fletcher marble suggests it had sustained pressure and temperature conditions that are greater than expected for Cambrian-Ordovician carbonates within the subthrust. Edelman and others (1986) indicate that peak metamorphic conditions affecting these rocks were no higher than greenschist facies during the Alleghanian deformation. Therefore, one of two situations may exist; the metamorphic gradient within the Paleozoic subthrust is greater than what was previously expected, or the protolith of the Fletcher marble predates Alleghanian deformation and metamorphism.

Carbonate Facies within the Tallulah Falls Metamorphic Suite

A proposed protolith for the Fletcher marble is a Neoproterozoic-Early Cambrian carbonate facies within the Tallulah Falls Metamorphic Suite akin to the Bandana marble. The Tallulah Falls Metamorphic Suite contains limited amounts of high-grade marble (Millington, 2006, Rankin, 1970, Rankin and others, 1973). In addition, the Fletcher marble and Brevard phyllonite contain amphibolite facies mineral assemblages that are similar to those in the Eastern Blue Ridge. Domains of protomylonite within the Fletcher marble bear similar grain size and mineralogy (>98% dolomite, trace tremolite) with that of the Bandana marble. The Bandana

marble and Fletcher marble may represent the portion of a larger Neoproterozoic-Early Cambrian metasedimentary sequence. Dismemberment of this platform could have been accomplished using Acadian-Neocadian fault systems such as the Brevard fault zone and the newly discovered Cradle-of-Forestry-in-America-fault (Dockal, 2007). The latter is located approximately 20 kilometers west of the study area, displays southwest dextral shear sense, and may have accommodated large amounts of lateral translation, stacking and thickening of the Tallulah Falls Metamorphic Suite (Dockal, 2007). If this did occur, it is plausible that the Fletcher marble protolith was transported great distances, and that the rock encompassing it would be retrograded from a high-grade sillimanite bearing metapelite, to the Brevard phyllonite. Subsequent deformation and metamorphism during the Alleghanian pervasively overprinted the earlier, higher-grade fabrics. Ductile-brittle transitional conditions produced the cataclastic fabrics in the marble. Brittle deformation preserves the last motions within the fault zone.

CONCLUSIONS

1. The Fletcher marble contains average composition of 66% dolomite, 13% calcite, 14% finely ground cataclastic material and 7% other minerals. The mineral assemblage contains dolomite + calcite + quartz + white mica \pm chlorite \pm talc \pm tremolite \pm wollastonite \pm graphite.
2. The Fletcher marble is a “marble protocataclasite” based upon the criteria established within the Science Language Technical Team Manual 1.0 (2004). The marble contains an early mylonite to protomylonite fabric in which >10% of the fabric is the product of tectonic grain size reduction. Cataclasis overprints this earlier mylonitic fabric, producing a protocataclasite fabric that retained primary cohesion and contains 10 to 50% cataclastic matrix.
3. The Fletcher marble has a polydeformed fabric that records several stages of development. The marble first sustained lower amphibolite facies metamorphism and crystal growth. Mylonitization is suggested by the presence of a lattice preferred orientation foliation, a grain-shape fabric, and a mica preferred orientation foliation. The color banding observed in outcrop is the mesoscale manifestation of the mylonite fabric. Cataclasis in the Fletcher marble represents a transitional change from ductile-brittle deformation in the rocks of the study area. Joint and shear fracture development occurred during continued brittle deformation along the Brevard fault zone. Last motion recorded is dip-slip to the northwest.

4. The Brevard phyllonite entrained the Fletcher marble and smaller “exotic” rocks during its early history. The Brevard phyllonite contains porphyroclasts and rock fragments that achieved amphibolite facies, sillimanite zone metamorphism during earlier higher-grade conditions. Lower amphibolite facies, assemblages are associated with conditions that favored tremolite crystallization. Greenschist to lower greenschist facies mineral assemblages are related to the Alleghanian orogeny.
5. The Fletcher marble contain domainal mineralogical features indicative of amphibolite facies conditions ranging from $500^{\circ}\text{C} \leq T < 610^{\circ}\text{C}$ and $500 \text{ Mpa} \leq P < 660 \text{ Mpa}$. Syntectonic veining contains wollastonite + talc + quartz \pm tremolite indicating a temperature range of 450 to 500°C , at a pressures less than 500 Mpa.
6. Given similar pressure and temperature conditions, dolomitic mineralogy and grain size of precursor fabrics, a Neoproterozoic-Early Cambrian carbonate facies containing rocks such as the Bandana marble, is proposed as a protolith to the Fletcher marble.

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APPENDIX. ECONOMIC GEOLOGY

Historical quarrying operations

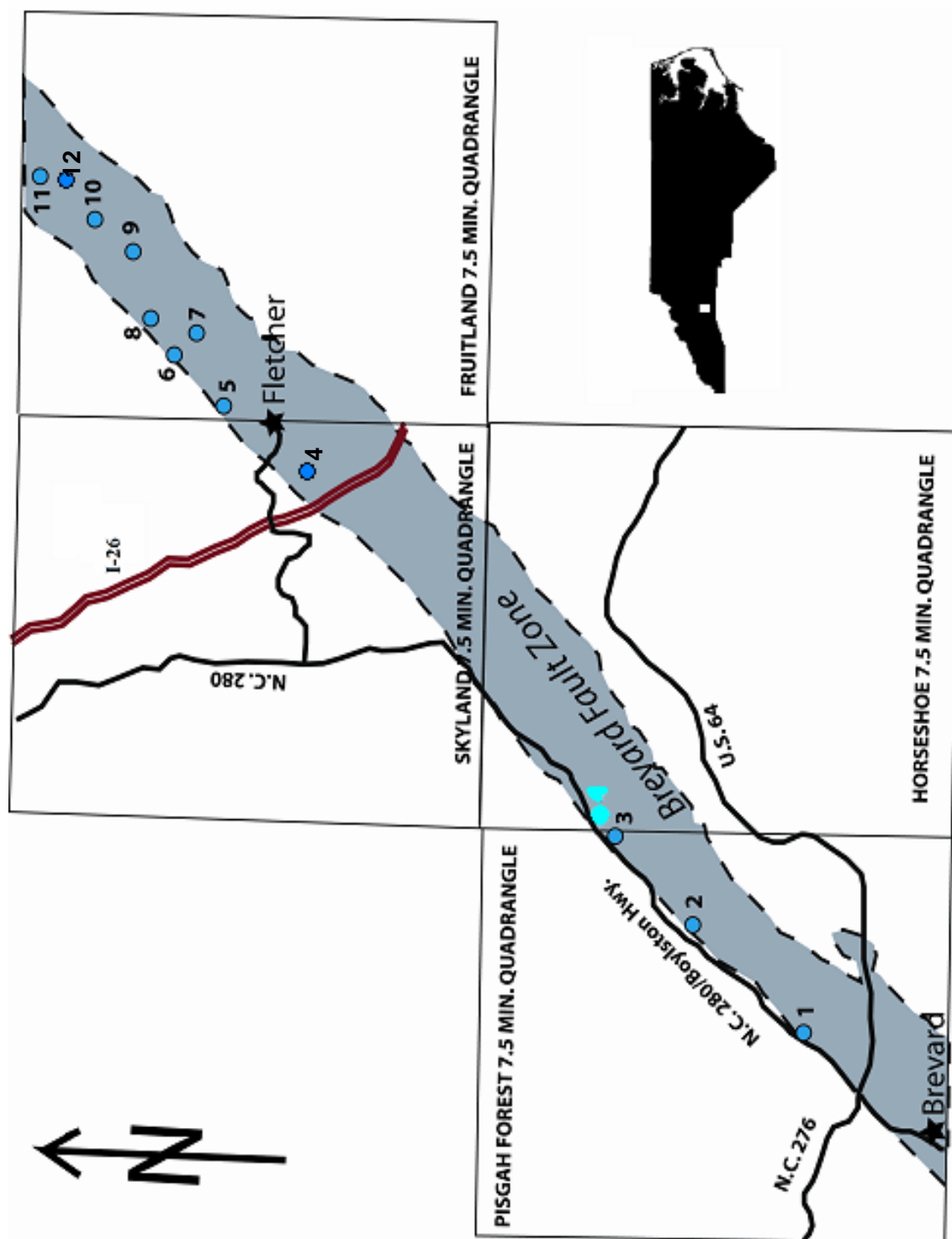
Brevard fault zone marble deposits have been the primary source for lime and crushed stone for surrounding Henderson, Transylvania, and Buncombe counties from 1835 to present (Conrad, 1960). Much of the marble, locally known as “blue limestone” or “white limestone” was burned in kilns to meet agricultural and construction needs of the local economy (Ingle, 1947). Agricultural lime or “ag-lime” enabled local farmers to maintain optimum soil pH values in soils. The lime was also used to make mortar for construction of many of the historical buildings in Fletcher, Brevard, and Asheville.

The marble deposits were often mined periodically depending upon the demand. The operations varied in complexity, most were workings involving small, shallow pits dug into a ridge side. Few were businesses with developed production facilities; often the rock was processed on site. Recovered stone was ground, sorted, burned in bee-hive kilns for 72 hours, pulverized by water slaking, and then shipped to market (Ingle, 1947).

Quarries and deposits northeast of Fletcher, N.C.

The northeastern most deposit of marble visited during the study is the Cane Creek-Brush Creek lens (Appendix, Figure 1; site 11, Table 1). It is located in the river bed and along the riverbank of the Cane Creek, beneath the Bush Creek River Road bridge, 200 meters southeast of the Cane Creek intersection. The carbonate is described as a 1.8 meter thick lens of medium grained, gray, slightly micaceous marble, exposed within

Appendix, Figure 1. Location map of documented marble deposits and quarries within the Brevard fault zone. Site 1: Currigan (Simms) quarry, Site 2: Baynard quarry, Site 3: Woodfin-Allison-Ezell localities, Site 4: Fletcher Limestone Company quarry and Cogdill quarry, Site 5: Piner Creek quarry, Site 6: Lower Christ School-Mills Gap quarry, Site 7: T.V.A. Exploratory boring, Site 8: Groves Lake quarry, Site 9: Tweed Nesbitt-Cane Creek lens, Site 10: Gravelly Creek quarry, Site 11: Cane Creek-Brush Creek lens, Site 12: T.V.A. Exploratory boring.



Site	Type Visit	Date	Quarry/Deposit Present?	References	Notes
1) Curritan (Simms) quarry	Reconnoiter	July 2000	No	Conrad, 1960 Ingle, 1947 Loughlin others, 1921	Overgrown abandoned
2) Baynard quarry	Site visit, reconnoiter	Oct 2001 Apr 2005	Not identified	Conrad, 1960 Ingle, 1947	Visit wrong locality. Could not contact landowner. Residential development
3) Woodfin-Allison-Ezell localities	Reconnoiter	Apr 2005	No	Watson and Laney, 1906, Conrad, 1960	Residential development
4) Fletcher Limestone Co. quarry	Study area	July 2001 Apr 2005	Active quarry	Watson and Laney, 1906 Ingle, 1947	Quarry dimensions 1021m long 145m wide 76m deep
Cogdill quarry	Site visit	2005	No-Flooded	Conrad, 1960 Kaltenbach, 2006a,b	Workings backfilled and graded. Flooded?
5) Piner Creek quarry	Site visit	Apr 2005	No	Ingle, 1947 Conrad, 1960 Lemmon and Dunn, 1973	Residential development
6) Lower Christ School-Mills Gap quarry	Reconnoiter	Apr 2005	No	Ingle, 1947 Conrad, 1960 Lemmon and Dunn, 1973	Boring logs
7) TVA boring	N/A			Lemmon and Dunn, 1973	Not visited
8) Groves Lake quarry	Reconnoiter	Apr 2005	Not identified	Ingle, 1947 Lemmon and Dunn, 1973	River level too high.
9) Tweed Nesbitt-Cane Creek lens	Reconnoiter	Apr 2005	Not identified	Lemmon and Dunn, 1973	Abandoned
10) Gravelly Creek quarry	Reconnoiter	Apr 2005	No	Ingle, 1947 Lemmon and Dunn, 1973	Could not sample: river height
11) Cane Creek-Brush Creek lens	Reconnoiter	Apr 2005	Identified	Lemmon and Dunn, 1973	Boring logs
12) TVA boring	N/A			Lemmon and Dunn, 1973	

Appendix, Table 1. Site information for carbonate deposits in the Brevard fault zone.

Sample	SiO ₂	CaO	MgO	Fe ₂ O ₃	R ₂ O ₃	Ignition	Total	Reference
Site 1	24.20	21.30	14.10	1.30	5.50	33.20	99.60	Ingle, 1947
Site 2	4.20	28.10	19.20	0.57	2.40	43.80	98.27	Ingle, 1947
Site 3								
Site 4 (b)	2.2	53.9	0.45	---	0.2	42.89	---	Conrad, 1960
Site 4 (w)	0.96	53.2	1.30	---	0.33	43.38	---	Conrad, 1960
Site 4 A	0.70	31.0	21.0	0.11	---	46.3		McDaniel, 1981
Site 5	1.10	31.50	19.00	0.17	0.50	46.50	98.77	Ingle, 1947
Site 5A	0.3	37.1	15.2	---	0.6	46.5	---	Lemmon, 1973
Site 5B	0.4	54.7	1.7	---	0.3	---	---	Lemmon, 1973
Site 6	0.80	31.80	18.90	0.17	0.60	46.30	98.57	Ingle, 1947
Site 6A	1.4	39.4	12.9	---	1.0	45.0		Lemmon, 1973
Site 7								
Site 8	0.20	32.80	20.00	0.10	0.60	46.80	100.50	Ingle, 1947
Site 8A	1.0	38.4	12.6	---	1.2	45.9	---	Lemmon, 1973
Site 9	---	19.2	1.03	2.14	---	---	---	Lemmon, 1973
Site 10								
Site 11	---	40.9	0.57	1.19	---	---	---	Lemmon, 1973
Shady Dol 1	4.7	29.0	20.3	0.58	0.93	44.4	100.46	Hatcher, 1971
Shady Dol 2	3.2	30.0	20.8	0.59	0.26	45.3	100.46	Hatcher, 1971
Shady Dol 3	1.0	29.7	21.4	1.7	0.51	45.8	100.28	Hatcher, 1971
Shady Dol 4	1.76	30.0	19.56	1.26	0.78	46.14	99.98	Hatcher, 1971

Sample	Mn	Cu	Sr	Zn	Pb	Fe	%Ca	%Mg	Reference
BFZ NC	450	0	1020	3	11	5900	29.22	0.89	Hatcher et.al, 1973
Site 9	440	2	700	30	8	15000	13.67	0.62	Hatcher et.al, 1973
Site 11	440	0	820	8	11	8300	29.22	0.34	Hatcher et.al, 1973

Appendix, Table 2. Geochemical analysis of major oxides and trace elements in Brevard fault zone marbles. Sample numbers correspond to site numbers in Appendix, Figure 1 and Table 1. All elemental values given in parts per million. Sample 'BFZ NC' was taken from an unknown marble deposit in Henderson County, NC.

Cane Creek (Dunn, 1973). The lens was observed within near the bank of the river; however the stage height of the river made direct study impossible.

Dunn (1973) reports that the Tennessee Valley Authority (TVA) drilled exploratory borings within Cane Creek for a proposed dam site (Appendix, Figure 1; sites 12 and 7, Table 1). Boring logs and cross-sections from the TVA indicate that 21 and 28 meters of steeply dipping marble were recovered from two of the boreholes (TVA, 1965, 1966). The cross-sections appear to indicate that the sampled marble lens may have a total thickness of 46 meters.

The Gravelly Creek quarry (Appendix, Figure 1; site 10, Appendix, Table 1) is reported to be 0.5 km southwest of the intersection of Cane Creek Road and Brush Creek Road (Lemmon and Dunn, 1973). Ingle (1947) mentioned that local residents knew of a quarry that had mined the “limestone” from a deposit during the late 1890’s. No remnants of the quarry or its workings exist today.

The Tweed Nesbitt Road-Cane Creek lens (Appendix, Figure 1; site 9, Appendix, Table 1) is mentioned in Dunn (1973) as a 1.8-1.9 meter thick zone of medium-grained micaceous marble exposed within the riverbed of Cane Creek. The lens could not be located during the course of the study due to flood stage of the river.

The Groves Lake quarry (Appendix, Table 1; site 8, Appendix, Table 1) is reported by Ingle (1947) and Dunn (1973) to be abandoned with little to no remaining kilns. Dunn (1973) reported collecting float samples for chemical analysis. A reconnoiter visit was attempted, however, the site was not found.

The Lower Christ School-Miles Gap quarry (Appendix, Figure 1; site 6, Appendix, Table 1) is an abandoned quarry site, 16 meters in diameter that is filled with water (Ingle 1947).

Conrad (1960) reports the kiln workings have been removed. Reconnoitering indicates that the site has been developed for limited residential use.

The Piner Creek quarry (Appendix, Figure 1; site 5, Appendix, Table 1) is located 0.9 kilometer northeast of the Baldwin Road-Cane Creek Road intersection. Access to the site is by an unimproved utilities service road adjacent to the railroad tracks. The site is largely overgrown and has been graded out; however, slumping is noticeable near the creek. An earthen levee is located 200-300 meters upstream of a culvert beneath the railroad tracks, which may have provided some flood control during quarrying operations. A trailer park, located 75-100 meters northwest of the railroad culvert, contains pond 7.5 to 7.6 meters in diameter, matching the excavation described by Ingle (1947) and Conrad (1960). No outcroppings of marble were located, however exposures of saprolitic biotite-white mica schist were observed 50 meters northwest of the site.

Quarries and deposits northeast of Brevard, N.C.

The Curritan (Simms) quarry (Appendix, Figure 1; site 1, Table 1) is located approximately 3.2 kilometers northeast of the N.C. 64-Ste Hwy 280 intersection. The site was worked in four places, where the marble is exposed in the northeast trending ridgeline (Loughlin and others, 1921, Ingle, 1947, Conrad, 1960). The marble is described to be blue, dolomitic, highly jointed and fractured, and of free of impurities (Conrad, 1960, Loughlin others, 1921). The deposit dips into the ridgeline at a steep angle, which made quarrying difficult due to the presence of large mounts of unstable overburden (Ingle, 1947). Reconnaissance of the site revealed no presence of the workings.

The Baynard quarry (Appendix, Figure 1; site 2, Appendix, Table 1) is located 1.4 kilometers southwest of the Transylvania-Henderson County line, 0.2 km southeast on an unimproved road, on private property. The landowner could not be reached in order to access the site. The site is described as the one of the oldest quarries in the area, having been worked prior to the Civil War (Conrad, 1960, Ingle, 1947). Ingle (1947) considered this site the best for lime production due to little overburden, volume of available marble, horizontal attitude of the deposit, and its elevation.

The Woodfin-Allison-Ezell localities (Appendix, Figure 1; site 3, Appendix, Table 1) are generally located 1.6 km northeast of the Transylvania-Henderson County line, on the east side of Ste. Hwy 280, within a valley, 0.2 km north of county road 1485. The entire site has been residentially developed, with no sign of the workings remaining. Watson and Laney (1906) describe marble quarried there generally as blue or white “limestone”. Conrad (1960) noted that these deposits generally tend to occupy topographic lows in the river valleys, strike of the marble deposits lie parallel to the trend of local streams, and that abrupt changes occur in dip inclination of the deposits.

The Cogdill quarry

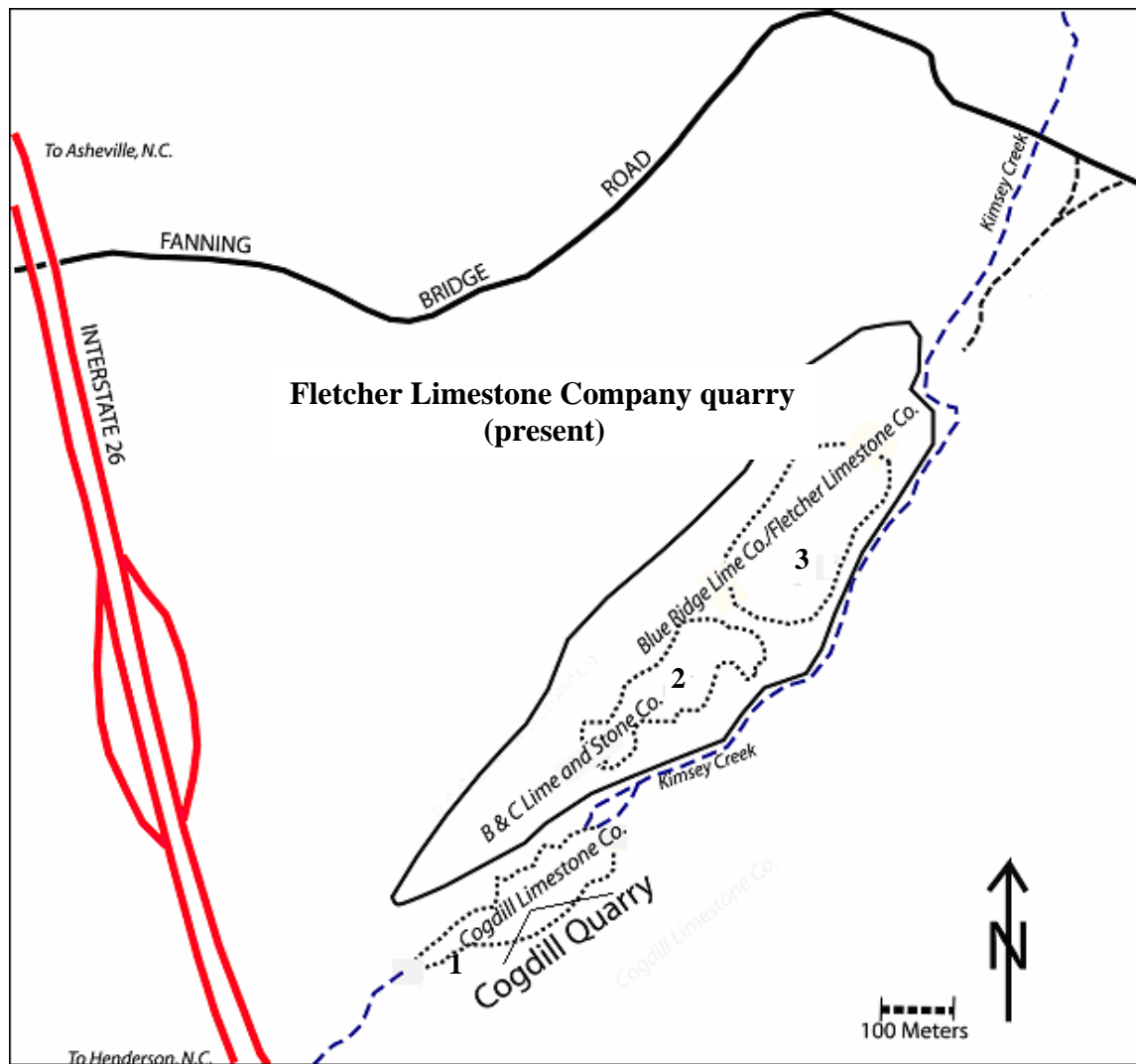
The Cogdill quarry (Appendix, Figure 1; site 4, Appendix, Table 1) is located on the Westfeldt property immediately southwest of the Fletcher Limestone Company quarry (Figure 1). The Cogdill quarry has been abandoned, and was later flooded in order to serve as a private recreation pond for the Westfeldt family. The Cogdill Limestone Company operated the quarry from 1946 to 1968, and quarried the southwestern side of the Fletcher marble deposit. The chief

product of the Cogdill Limestone Company was dolomitic road metal and concrete aggregate (McDaniel, 1981).

The Blue Ridge Lime Company and B&C Lime and Stone Company operations

Three companies have historically worked the Fletcher marble deposit (Appendix, Figure 2): the Blue Ridge Lime Company, the B&C Lime and Stone Company, and the aforementioned Cogdill Limestone Company (Conrad, 1960). The property owners, the Lance and Westfeldt families, have licensed quarrying of the marble since 1835. This generated an intense rivalry between the Lance family, who owned the northeastern portion of the Fletcher quarry and Piner Creek quarry, and the Westfeldt family who owned the surrounding lands (John Brooks, Fletcher Limestone Company, personal communication).

The Blue Ridge Lime Company was the first to commercially develop the Fletcher quarry in 1904. The company worked what is today the northeastern most portion of the Fletcher quarry. The majority of the operation was on the Westfeldt property, however, expansion to the northeast was conducted under lease agreement with the Lance family (Loughlin and others, 1921). The B&C Lime & Stone Company operated the central portion of the present-day quarry. The company produced lime and crushed stone from 1926 to 1936 (Conrad, 1960; McDaniel, 1981). Both companies were purchased by the Fletcher Limestone Company in 1936 (Conrad, 1960; McDaniel, 1981), which later became incorporated in 1948. Bob Stevens, a monument company owner from Mount Airy, N.C., purchased stock in the Fletcher Limestone Company, Inc., in the



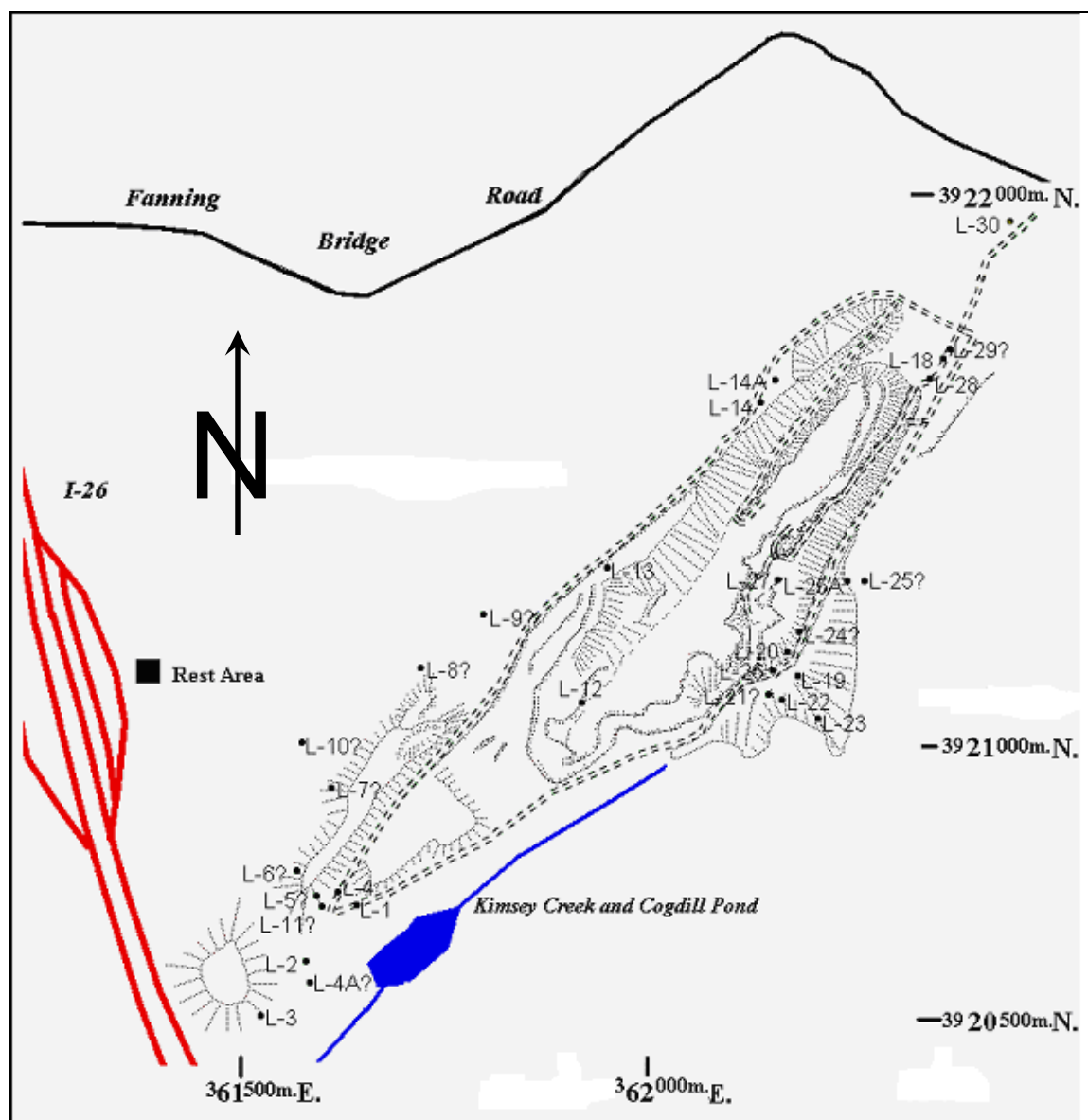
Appendix, Figure 2. Historical quarrying operations within the Fletcher marble deposit.

1. Cogdill Limestone Company, 1946-1968.
2. B & C Lime and Stone Company, 1926-1936.
3. Blue Ridge Lime Company, 1904-1936.

late 1970's. By 1999, Mr. Stevens had purchased the entire share of the company and became its sole owner (unpublished information, Fletcher Limestone Company, Inc.). Presently, the company is owned by Ms. Barbara Stevens and operations are supervised by Mr. John Brooks.

Development of the Fletcher Limestone Company quarry

The Fletcher Limestone Company currently operates the majority of marble deposit southwest of Fletcher, N.C. The quarry pit workings had a total recorded length of 92 meters along strike, a width of 76 meters, and a maximum depth of 12 meters in 1918 (Loughlin and others, 1921). Today the Fletcher Limestone Company quarry dimensions are roughly 1021 meters long, 145 meters wide and 76 meters deep. The Fletcher Limestone Company consulted Robert T. Wall, a private geologist, to estimate the volume of "limestone" within the quarry in 1978. Approximately 38 borings were drilled on the quarry property to determine the extent of the marble body (Appendix, Figure 3). The drilling records from Mr. Wall's report indicate that the marble deposit dips to the southeast, and no additional marble is present to the northwest. Estimates for the volume of rock present within the quarry were 277,923 cubic yards based upon 1978 survey information. Mr. Wall recommendation was for company to expand their excavations east, to expose an additional 191,555 cubic yards for development.



Appendix, Figure 3. Location map of L-series exploratory borings drilled in 1978 by Mr. Wall and Company for the Fletcher Limestone Company.

Operations

Quarrying of the marble within the Fletcher quarry is largely done by mechanical means. Operators use front-end loaders, tracked backhoes, and heavy haulers to excavate the marble and transport it from the pit workings to the plant. The highly fractured and cleaved nature of the stone makes excavation by machinery easy. Blasting, which used to be conducted in order to excavate overburden away from the southeastern wall to expose marble, was not observed during this study. The Fletcher Limestone Company is currently undergoing growth and reorganization to meet the challenges of competing with southeastern and global companies to provide aggregate and calcium carbonate. In order to economically exploit more of the deposit, the company undertook a major site reconfiguration, in accordance with Mr. Wall's suggestions. The Kimsey Creek was diverted and a pumping system was emplaced to prevent the flooding of the quarry. In addition, new facilities have been purchased by the company. Two crushers and a screening plant produce a fine consistency stone, and a laboratory has been added. Two additional silos were delivered to the Fletcher Limestone Company during March 2005, and an additional screening plant is planned for construction.

Products

The quarry traditionally produced agricultural lime, crushed stone and aggregate for construction and road metal. Decorative stone is also successfully marketed because of the attractive brightness and crystalline nature of the marble. It is offered in two sizes, $\frac{3}{4}$ " and $\frac{3}{8}$ ", which was quoted at \$23.50/ton. The plant manager, John Brooks expanded the product line, by offering a variety of extremely fine (3-22 micron) calcium carbonate powder, named "Glacier White". "Glacier White" is a high purity carbonate powder, which has various applications in

agriculture, civil engineering, water management, chemical production, and steel industry. The Fletcher Limestone Company offers “Glacier White” in 50 lbs bags, super-sacks, and in bulk for \$0.05/lbs.

Processed spoil material is marketed for quality foundation fill for the State Government and local contractors. “Road-Bond” is comprised of clayey phyllonite overburden and marble screenings; once compacted, it forms a stiff soil foundation for roadways, and small buildings. “Road-Bond” is quoted to cost \$23.50/ton and is immediately ready-to-use as fill material.

BIOGRAPHICAL SKETCH

Kelley J. Kaltenbach was born on September 26, 1972 in Marion, Ohio. He enlisted into the Army National Guard in October 1997 with the rank of Private First Class. He graduated from the Ohio State University in May 1998 with a B.S. degree in Geology, with a special focus in geophysics. He worked as a field geologist with BBC & M Engineering from 1998 to 1999. In 1999, he entered the graduate program in Earth Sciences at the University of North Carolina Wilmington where he worked under the direction of Dr. James D. Dockal. During his graduate career, Mr. Kaltenbach attended the Officer Candidate School at Fort Bragg, North Carolina, and was commissioned a Second Lieutenant on August 4, 2001 within the North Carolina Army National Guard. Second Lieutenant Kaltenbach completed the Armor Officer Basic Course April 2, 2003, and successfully commanded his tank platoon during his unit's mission at the National Training Center, Fort Irwin, California. Second Lieutenant Kaltenbach served in Operation Iraqi Freedom as a Platoon Leader in C-Company 1/252AR, where he was promoted to First Lieutenant and awarded the Army Commendation Medal for his actions during combat operations against enemy forces. First Lieutenant Kaltenbach was assigned Executive Officer, A-Company, 1/252 Armor on August 14, 2005 and later assumed command of D-Company, 1/120th CAB on September 24, 2006.

Kelley graduated from the University of North Carolina Wilmington with a M.S. Degree in Geology. He currently works as a civilian employee at the Wilmington District Corps of Engineers and has assisted in several geotechnical projects targeted to benefit the nation and the people of North Carolina.